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Articles by OUGS Members,
the Annual Report for 2020
and the 2020 Moyra Eldridge Photographic Competition Winning and Highly Commended photographs

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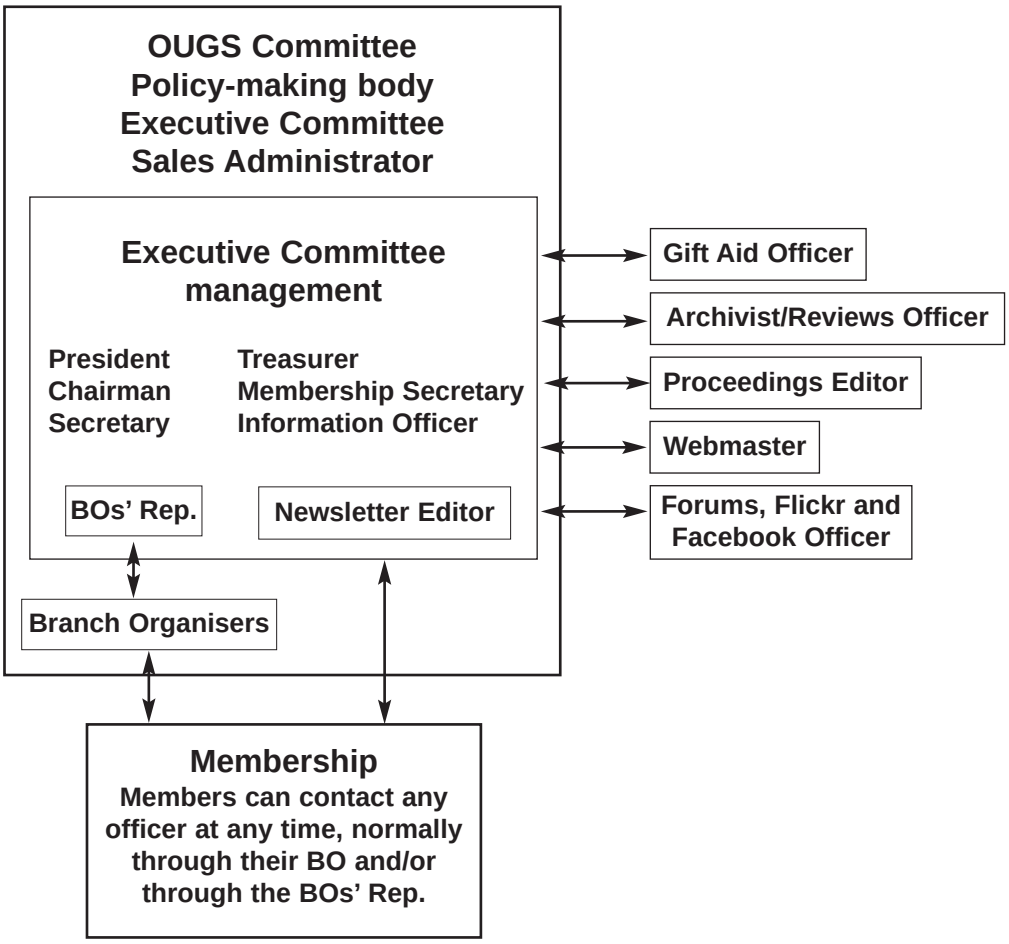

Editorial:

Dear readers,

There is no denying that 2020 was an unusual year.

Not only were all our OUGS activities cancelled, rescheduled, curtailed, or relegated to being held on Zoom, but the second series of official Major League Baseball ⚾ games in London — the results of which were to be included in the MLB 2020 seasonal standings — were cancelled too! 😩 *And in case you are wondering, the weekend of two games, for which I had tickets to go to with my son (the other Dr Jones), were to feature the Central Division National League Chicago Cubs (the 2016 World Series Champions) and the St. Louis Cardinals (the 2011 World Series Champions). We were so looking forward to watching my old Dad's / Grandad's home team birds whup those cubs!*

Anyway, we held no spring OUGS AGM, which was to be held in the beautiful city of Glasgow, with its wonderful art galleries; we could not hold our OUGS Annual Symposium, which was to be held at the University of Lancaster; and all geological field trips were cancelled, postponed or otherwise held in limbo. Even the London Geological Association's annual Day of Geology had to be held on Zoom.

Therefore, the big question for your dedicated Editor became: Where on Earth am I to get articles to publish for my fellow members to read in their OUGS Proceedings *for 2020?*

Well, it turns out, I need not have fretted. The call went out and members from branches all around the Society came forth offering an amzingly varied collection of 16 articles. Not only does this stepping forth into the breach represent much appreciated help to your Editor, but it also demonstrates the wide geological interests of our membership.

I am most gratedful to you all for your contrbutions. And as it appears that our Annual Symposium has had to be postponed again for 2021, I woud like to call for articles again now. There are even two or three articles already potentially in the wings.

In addition, publishers of Earth science books have again been most generous to us through the past year. Seven different pubishers have sent me 21 books for review. Once again, on behalf of the Society, I am most grateful to them all for their generosity.

Last year The Open University celebrated its 50th birthday. The dedicated staff of the university continue mto development and mould the curriculum. We very much value our close association with The OU School of Environment, Earth and Ecosystem Sciences (EEES). For its most recent evololution see our new President Angela Coe's report on degree changes, new courses and much else in the OUGS Annual Report for 2020*, bound together with the* Proceedings *after the section on our 2020 Moyra Eldrige Photographic Competition winning and highly commended photographs.*

While the Coronavirus Pandemic can hardly be said to be a pleasant experience, let us look at some bright spots in 2020: The sterling performance under extremley difficult times by our UK NHS; the fantastic cooperation of scientists around the world to develop vaccines in record time; and not least the seeing off, at last, of he who shall not be named, but who is a meanace to science and society.

It only remains for me, as always, to wish you happy reading. Let us look forward to further adventures and reading in the Earth sciences.

— David M. Jones, OUGS Proceedings Editor

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The Editor would like to give his sincere thank-you to fellow OUGS Members who gave him invaluable help with all aspects of this issue of the *OUGS Proceedings*: to the authors for their cooperation and timely responses to my many editorial queries; to OUGS President Susanne Schwenzer, her successor as President Angela Coe, OUGS Chairman Sue Vernon, OUGS Secretary Don Cameron, and his successor as Secretary Pauline Kirtley for their advice and encouragement; to OUGS Member Rosemary Darby for her diligent proofreading; and to OUGS Family Member Anne Jones for her suggestions and advice regarding layout and design.

Geological time periods

Michael Perkins

We are all accustomed to dividing geological time into eras, periods and stages without a moment's thought. But where did those divisions come from? Who were the geologists who named our geological divisions, and why? I would like to explore the origins of the names of our geological time periods, looking at those responsible for the names we use so often, and the work and discoveries that led them to classify rocks in this way. Let's start with the most recent, and work back through time.

The Cenozoic Era

First of all, should we write Cenozoic, Cainozoic, Caenozoic, Cænozoic, or even Kainozoic? And how is it pronounced? As you will recall from your first OU geology course, the name derives from the classical Greek, meaning 'recent' or 'new life'. Since the first syllable comes from *kainos*, you would expect it to be a hard 'c' sound. In fact, either a hard or soft 'c', and a variety of following vowel sounds give an acceptable pronunciation, so you won't really go much wrong. Nonetheless, the International Commission on Stratigraphy (ICS) has opted to simplify the spelling to 'Cenozoic', and so the soft 'c'ed , as in 'Sen-o-zo-ic', seems the preferred option for today's ears. In any case, since I will rely on the ICS for the most up-to-date data on the geological time scale[1], I will also defer to them on the preferred spelling. Cenozoic it is.

The term is assumed to have been coined by the English geologist John Phillips (Fig. 1), who first used it in print in 1840. John Phillips was a friend of William Smith and did most of his important work in Yorkshire. Funnily enough, he originally spelt the era 'Kainozoic'.

> *As many systems of combinations of organic forms as are clearly traceable in the stratified crust of the globe, so many corresponding terms (such as Palaeozoic, Mesozoic, Kainozoic &c.) may be made.*[2]

The fact that this occurs in an encyclopaedia entry in such a throwaway fashion makes me suspect the term had already been in use. It is likely that Phillips himself had been using it since at least 1838, and it may have also been being used by Sedgwick.

Of course, the start of the Cenozoic is marked by the K-T boundary — or more properly the K-Pg boundary. The Global Boundary Stratotype Section and Point (GSSP) is in Tunisia, marked by the iridium anomaly associated with the Chicxulub meteor impact in the Caribbean Sea off the coast of Yucatan.

Periods of the Cenozoic Era Traditionally, the Cenozoic comprised the Tertiary and Quaternary Periods. However, the Tertiary has been frowned upon for some time and is no longer used in the ICS timescale. The Quaternary also lost its status as a Period for a few years, but has now been reinstated. So officially, the Cenozoic is divided into the Paleogene, Neogene and Quaternary Periods, though it is unclear whether the last of these is here to stay or not.

The Quaternary is therefore the last stand of the system introduced by Giovanni Arduino in Italy (Fig. 2). Like some other scientists of his time (such as Pierre Simon Pallas), Arduino

Figure 1 John Phillips (1800–1874).

first divided rocks into the Primary, Secondary and Tertiary series. But then he added a fourth type in 1759, which stays with us today, for very recent sediments found with organisms alive today.

> *Il primo di detti ordini, cioè il più profundo, ed il secondo, che al primo succede, formano le grandi montagne, dei monti, e dei colli; il terzo costituisce solamente dei picciolo monti, e colli: el il quarto le pianure.*[3]

Figuer 2 Giovanni Arduino (1714–1795) The 'Father of Italian Geology'.

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The terms reflecting this classification into four distinct divisions was picked up (or coined independently) over the following years and has persisted to this day, despite many attempts to relegate it to history.

Preceding the Quaternary come the Neogene and Palaeogene. These terms, also derived from classic Greek, were first coined by the Austrian palaeontologist Moritz Hörnes in 1853, and mean 'new born' and 'old born'. The period distinction was based both on differences in the mollusc fauna and on facies changes as the boundary between them is crossed:

> *The frequent occurrence of Viennese mollusks in typical Miocene as well as in typical Pliocene deposits motivated me — in order to avoid the perpetual monotony [of providing] details about the deposits — to subsume both deposits provisionally under the name 'Neogene' ... in distinguishing contrast to the Eocene.*[4]

Epochs of the Cenozoic Era The epochs from the Neogene onwards are further examples of names derived from classical Greek words, and all use the suffix '-cene', which as we have seen means 'new' or 'recent'. So we have the Palaeocene ('old recent'), Eocene ('dawn recent') and Oligocene ('few recent') in the Palaeocene, and the Miocene ('less recent') and Pliocene ('more recent') in the Neogene. While these '-cene' names have proliferated since their original definitions, their conception goes back to Charles Lyell (Fig. 3), who in his *Elements of Geology* (the final volume of his three-volume *Principles of Geology*) drew upon the work of Gérard Paul Deshayes on molluscs of the Paris Basin. Lyell proposed the terms depending on the percentage of fossil invertebrates that are still living. While his quantitative boundaries were arbitrary, they evidently record important faunal transitions between the strata.

Lyell also named the Pleistocene ('newest recent'), for the even more recent strata that he discovered on Sicily — though he originally called these strata the 'Newer Pliocene'. Summarising, he wrote:

Figure 3 Charles Lyell (1797–1875).

> *For the sake of clearness and brevity, I proposed to give short technical names to these four groups, or the periods to which they respectively belonged. I called the first or oldest of them Eocene, the second Miocene, the third Older Pliocene, and the last or fourth, Newer Pliocene. The first of the above terms, Eocene ... because the fossil shells of this period contain an extremely small proportion of living species, which may be looked upon as indicating the dawn of the recent or existing state of the testaceous fauna.*[5]

Nowadays the boundaries are pinpointed using specific microfossils and carbon isotope excursions rather than by percentages of extant species.

Finally, we of course have the Holocene in the Quaternary, which means 'wholly recent'. The Holocene is unique in that its start is defined not by a horizon in the rock record, but in an ice core record from Central Greenland. In addition, recent attention has focused on whether we should now also define an Anthropocene epoch. This has not yet been formally recognised, and various proposals exist for where it should start. The spike in radionuclides resulting from atomic weapon testing, or the beginning of the industrial revolution are common suggestions, but a convincing argument is made for the Orbis Spike, a carbon excursion resulting from the drawdown of carbon dioxide after the colonisation of the Americas, which additionally marks the worldwide interchange of species and the start of modern global trading.[6] The naming, although it fits the '-cene' family, sounds a bit weird when translated: 'human recent'.

The Mesozoic Era

The Mesozoic, 'Middle Life' is easy enough. As we saw above, the term came from John Phillips. But in the quotation from the *Penny Cyclopaedia*, he did not limit the naming to only three eras. There are, after all, five major extinction events generally recognised: the Ordovician-Silurian and Late Devonian events within the Paleozoic, the Permian-Triassic event at the end of the Paleozoic, the Triassic-Jurassic event within the Mesozoic, and of course the Cretaceous-Paleogene event at the end of the Mesozoic. So it is interesting that only two of these define Era boundaries, despite others being at least as big as the K-T event.

The three eras were defined by reference to existing animal groups. Many of the families of the Palaeozoic are now extinct, but a smaller number of those of the Mesozoic are no longer with us. This is reflected most visibly in the macro- and megafauna, with the clichéd Age of Reptiles often being used to define the Mesozoic. Nonetheless, perhaps the most obvious victim of the end Palaeozoic extinction was the humble trilobite. Interestingly, the periods contained in the three eras changed over time. The Palaeozoic originally included just the Cambrian, Ordovician and Silurian, but was gradually expanding to engulf the Devonian, Carboniferous and Permian as well.

Periods of the Mesozoic Era The Mesozoic periods comprise the Triassic, the Jurassic and the Cretaceous. The first of these comes from the 'Trias', named by Friedrich August von Alberti and referring to a characteristic set of three layers (red beds, the *Muschelkalk* limestone, followed by shales) found throughout Germany.

Figure 4 Jean Baptiste d'Omalius d'Halloy (1783–1875).

The Jurassic refers to the Jura Mountains. This term has its origins in the work of French geologist Alexandre Brongniart (1770–1847), who built on the observations of Alexander von Humboldt (1769–1859, the Prussian polymath, geographer, naturalist and explorer) in the area.

Finally, the Cretaceous refers to the Latin 'creta' meaning chalk. This name was coined by Belgian geologist Jean Baptiste d'Omalius d'Halloy (Fig. 4).

> *La troisième, qui correspond à ce qu'on a déja appelé formation de la craie, sera désigné par le nom de terrain crétacé.*[7]

A believer in evolution (modification by descent) before Darwin, and a geological map-maker surveying France at roughly the same time that William Smith (1769–1859) was working in Britain, he was clearly a geological pioneer.

Epochs of the Mesozoic Era The official epochs of each of the periods in the Mesozoic are the rather uninspiring: Lower, Middle and Upper, though those who have studied OU S339 and similar courses will be familiar with the 12 stages that make up the Cretaceous Period. These have another history of their own.

The Palaeozoic Era

When he wrote his *Penny Cyclopaedia* article John Phillips himself recognised that the term Palaeozoic was already being used by Sedgwick (about 1838), so it seems likely that it had gained traction in scientific parlance before it was first committed to print.

Periods of the Palaeozoic Era The Palaeozoic periods comprise the Cambrian, the Ordovician, the Silurian, the Devonian, the Carboniferous and the Permian. The first three terms were the cause of a heated debate between Adam Sedgwick (1785–1873) and Roderick Murchison (1792–1871). Sedgwick coined the term Cambrian based on his work in Wales (Cambria is the Latin name for Wales). Murchison named the Silurian after the Silures tribe.

> *I venture to suggest, that as the great mass of rocks in question, trending from south-west to north-east, traverses the kingdom of our ancestors the Silures, the term "Silurian system" should be adopted.*[8]

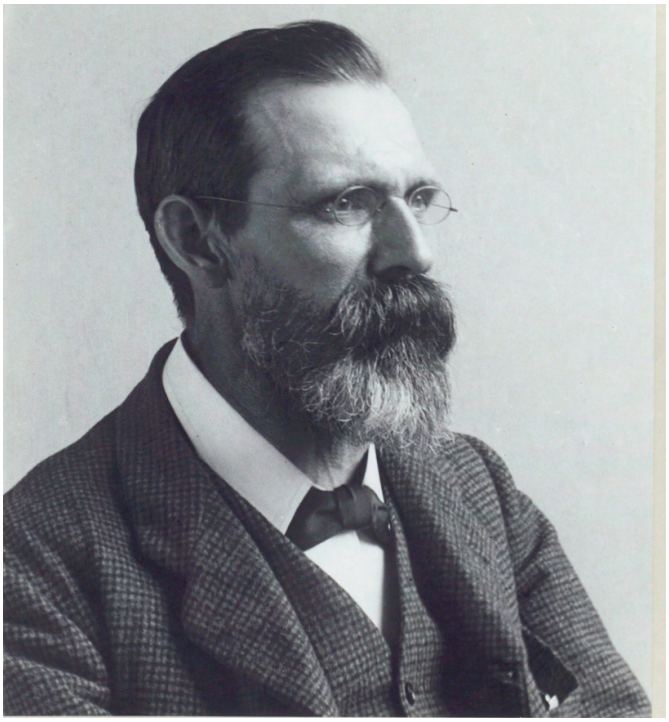
Nonetheless, a quick glance at a tribal map of Britain shows that the Silures probably lived mostly in the Carboniferous coalfield areas of Southern Wales.

A bitter dispute broke out between them regarding what to do with the intervening strata. the fauna of which bear some similarities to those in the earlier Cambrian rocks while also having features in common with the later Silurian fossils. Murchison wanted to claim them for his Silurian Period (and while he was at it, why not subsume the Cambrian too?); while Sedgwick wished to bring them under his Cambrian jurisdiction.

It took Charles Lapworth (Fig. 5) to see the obvious solution: that the intermediate rocks were sufficiently different to warrant a third Period, named after the Ordovices tribe of North Wales:

> *North Wales itself ... lay within the territory of the Ordovices; a tribe as undaunted in its resistance to the Romans as the Silures. It was indeed the last of the old British tribes to yield to their invincible legions; and it is consequently quite as well worthy of scientific commemoration as the Silures themselves.*[9]

Figure 5 Charles Lapworth (1842–1920).



Of course, we are lucky to have the defining GSSP for the base of the Silurian in Scotland, at Dob's Linn near Moffat (Fig. 6).

The Devonian, funnily enough, was again named by Sedgwick and Murchison, and again after a bitter dispute. However, in this case they were both on the same side, against Henry De la Beche (1796–1855) and George Bellas Greenough (1778–1855). This 'Great Devonian Controversy' resulted from the discovery of plant remains in what seemed to be Silurian strata. It was not until similar fossils were found in a more complete succession in Russia that it was accepted that a new Devonian Period was justified.

The Carboniferous (or 'coal-bearing') Period was named by William Conybeare (1787–1857) and William Phillips (1775–1828; no relation of John Phillips) in 1822. We are lucky that the Carboniferous caught on. Their first choice was the anodyne 'Medial':

> *For this order we have proposed the name of Medial wishing to adopt an appellation entirely free from theory, and indicating only the central place of this group in the fivefold division of the geological series which results from assigning to it a separate class. The epithet carboniferous is of obvious application to this series.*[10]

The final period of the Palaeozoic is the Permian. This was another Murchison invention. In 1840, Murchison undertook a geological exploration of Russia. The term 'Permian' saw the light of day in 1841, and refers to the region around Perm, close to the Ural Mountains.

> *The carboniferous system is surmounted, to the east of the Volga, by a vast series of beds of marls, schists, limestones, sandstone and conglomerates, to which I propose to give the name of "Permian System," because, although this series represents as a whole, the lower new red sandstone (Rohte todte liegende) and the magnesian limestone or Zechstein, yet it cannot be classed exactly… with either of the German or British subdivisions of this age.*[11]

Epochs of the Palaeozoic Era The official epochs of the Palaeozoic Era are a hodge-podge. Unsurprisingly, the Silurian names mostly come from type localities in Wales or the Marches (Llandovery, Wenlock and Ludlow), with the exception of Pridoli, which comes from a locality in Czechia.

The localities that give rise to epochs of the Permian are in China (Lopingian), New Mexico (Guadalupian) and, of course, Russia (Cisuralian).

In the Cambrian we have the Terreneuvian, the Miaolingian and the Furongian. The first of these refers to a locality in Newfoundland. The other two come from China: the Miaolingian Mountains in Guizhou Province and from the Chinese word for 'lotus', referring to the 'Lotus State', Hunan. The Cambrian also contains the mundanely titled 'Series 2', which is yet to receive a more interesting name.

The Devonian and Ordovician periods are both divided into epochs officially called the Lower, the Middle and the Upper.

The Carboniferous is more complex, with different names in Europe and America. American geologists use the terms 'Pennsylvanian' and 'Mississipian', while European geologists use Dinantian and Silesian, respectively. Stage names that are familiar to us (e.g. Namurian and Westphalian) are likewise not used globally.

Figure 6 Dob's Linn — the base Silurian GSSP.

References and sources

Much of the information for this article came from Wikipedia entries; specifically, the pages referring to the Eras and Epochs, as well as those describing the lives of the geologists involved. The following sources have been quoted in the article:

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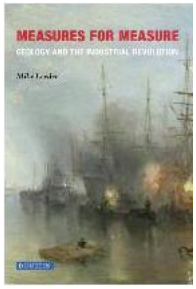
Book review



Leeder, Mike 2020 *Measure for Measure: Geology and the Industrial Revolution*. Edinburgh: Dunedin Academic Press (ISBN 978-1-780-46081-9; i–xii + 339pp; hardback £24.99)

The book explores the possible reasons for why the Industrial Revolution began in earnest in the late 18th century in Great Britain rather than in any other similarly developed place in the world. In addressing that question the first section of the book provides a short history of those early days of industrial development, which reads not as a dry text, but instead like a 'whodunit', making it a veritable page-turner.

Without offering any more of a spoiler than the title suggests, coal and iron ore were interrelated factors, and the second section of the book sets out a geological timeline relating the evolution of land plants to the shifting positions of continental landmasses. Furthermore, explanations for how extensive deposits of those commodities were deposited and preserved under the British landscape rather than becoming lost through erosion, etc are given. Although this lacks the pace of the opening section, it offers a clear sequence progression for the formation of Pangea that should be accessible to all; and it certainly made a few parts of the coal story clearer to me.

The third section of the book explores the cultural and historical legacy of the Industrial Revolution, as well as offering an answer as to why the birthplace was in Britain — and the story is not perhaps what you have been told or might imagine. However, I found this section offered mixed messages: on one hand extolling particularly the cultural legacy, such as William Turner's paintings of industrial landscapes, hazy and fired by the colours of heavy industry, while simultaneously evaluating historical activities and their environmental impacts in the context of what has become apparent only in recent times.

The fourth section is something of a gazetteer exploring each of the principal coalfields of the UK in turn. For each, the underlying coal and iron geology is related to the industrial developments manifested within the region that used these resources, and developments that followed to enable greater exploitation of the resources and production of a wider range of materials.

While the emerging technologies are explained in detail — for example the development of the Bessemer Process — there is perhaps a lack of basic foundation, and I was compelled to look elsewhere for the basics of iron production: for example, what is 'pig iron' and why it needs to be refined before it can be made into useful items. For each region, however, the story closes the same way — with the exhaustion of resources both physical and economic, which after 200 years brought to an end the role of Great Britain at the forefront of heavy industry.

The quality of the book is exceptional, with numerous concise tables, figures and diagrams, and excellent reproductions of drawings and photographs — all the better for the use of semi-gloss paper, which fully justifies the cover price.

Overall I believe this book expertly treads the fine line between over technical and over simplification, putting it well within the grasp of any reader who has ever wondered why a small island with no long-standing technical cultural history suddenly became the literal engine driving the world's industry forward.

— Chris Popham, OUGS South West Branch Organiser

Peperites: products of magma-wet sediment interaction

Duncan Woodcock

1 Introduction

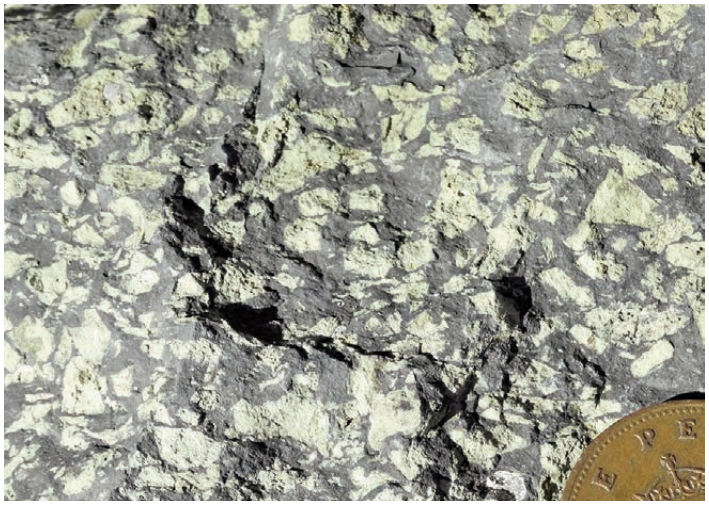
In geology texts, a sill or dyke is often depicted as the product of a body of magma intruding a lithified sedimentary country rock (e.g. Grotzinger and Jordan 2010, 104). Such an intrusion features upper and lower chilled margins together with adjacent baking of the host rock. Similarly, we usually think of a lava flow erupted onto a dry substrate. In both cases, interaction of magma with the country rock or substrate is primarily thermal, with heat transferred by conduction.

In contrast, an intrusion at a high level in the crust may be emplaced into wet, unconsolidated sediments. Similarly, a lava flow may be erupted over wet sediments. In these instances, interaction between magma and host is usually much more vigorous, with magma fragmentation together with heat transfer by convection within transiently mobilised sediment. The disruption of both magma and sediment at the magma-sediment interface results in a type of sediment-matrix igneous breccia known as a peperite.

Peperites are thus rocks formed essentially *in situ* by disintegration of magma interacting and mingling with unconsolidated, typically wet sediments (White *et al.* 2000). They provide evidence that magmatism occurred soon after the deposition of the sediments. Peperites have developed from magmas over the full range of composition, from rhyolitic (e.g. Hunns and McPhie 1999) to basaltic (e.g. Fig. 1). They occur within a wide range of host sediment types, including both carbonate (Fig. 2) and clastic (Doyle 2000) sequences.

The majority of studies in the literature describe peperites on the margins of intrusions; however, a number of studies have described peperite formation at the base of lava flows (e.g. Waichel *et al.* 2007; Rawcliffe and Brown 2014), and where lava flows have locally burrowed into the underlying sediments (Brown and Bell 2007). Peperites can also develop at the base of pyroclastic density currents if welding is sufficiently intense (Branney *et al.* 2008).

Figure 1 Altered basaltic clasts in mudstone matrix within a peperite at Carraig Mhor, Carsaig, Mull (NM 566 211).



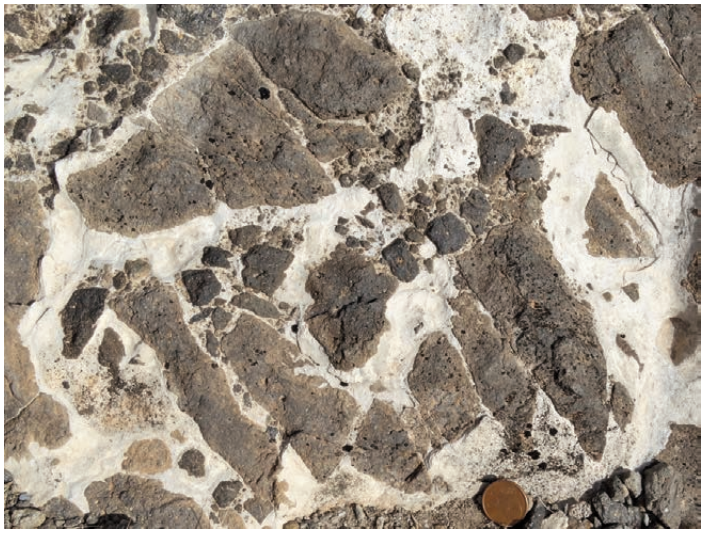


Figure 2 Clasts of lamproite in carbonate matrix, Cabezo Maria, Almeria, Spain. This peperite was formed by intrusion into wet carbonate sediments.

2 Peperite-forming processes

Peperite formation involves the fragmentation or disintegration of magma to form juvenile clasts, together with the mingling of these clasts with the host sediment. These processes can occur simultaneously or sequentially.

(i) Magma fragmentation

Skilling *et al.* (2002) list several possible fragmentation mechanisms. Brittle fragmentation mechanisms include quenching, autobrecciation and explosion, while ductile mechanisms include fluid shear and various instabilities at the magma-sediment interface. In general, more than one mechanism can operate to produce a given peperite.

Brittle fragmentation is favoured by high deformation strain rates, which can be produced by thermal contraction in response to rapid chilling, or by explosive magma-water interaction (Wohletz 1983). Brittle fragmentation is considered to produce blocky peperites (Busby-Spera and White 1987; Squire and McPhie 2002). In 2D exposures, blocky peperites comprise polygonal clasts with straight to slightly curved edges (Fig. 3, *overleaf*). These clasts may show varying degrees of jigsaw fit (Fig. 4, *overleaf*), suggesting an *in situ* fragmentation process.

Ductile fragmentation is favoured by low magma viscosity and/or low strain rates. It is most likely to occur during film boiling, when the magma is, to some degree, 'insulated' from the wet sediment by a vapour film (Woodcock *et al.* 2012). Ductile fragmentation is considered to produce fluidal peperites (Squire and McPhie 2002), which comprise clasts with a globular or irregular outline. Ductile fragmentation can be produced by shear associated with the emplacement of magma into wet, unconsolidated sediment. It can also be produced by a range of instabilities at the magma-sediment interface induced by gravity (Rayleigh-Taylor instability) or by instabilities associated with the boiling process.

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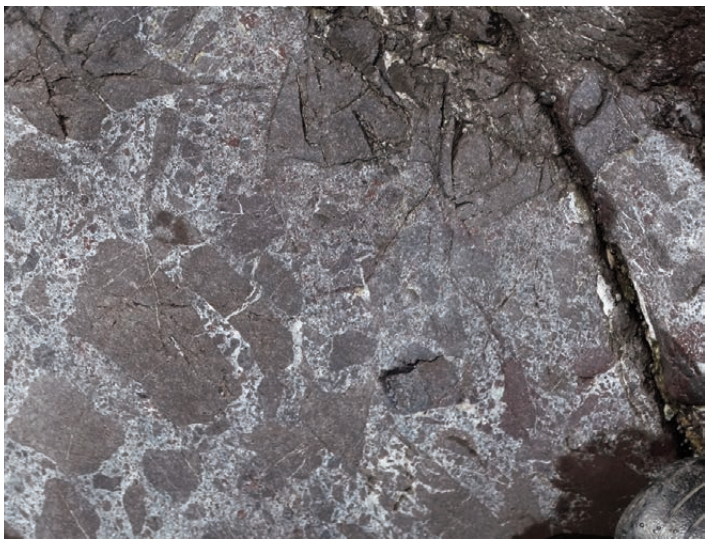

Figure 3 Blocky peperite at Port a Chroinn, Kerrera, (NM 809 264) (field of view 100mm ¥ 150mm).

(ii) Mingling of clasts and sediment

Skilling *et al.* (2002) identify several clast-sediment mingling mechanisms. These include dispersion following explosions and magma-sediment density contrasts. Most rely on the transient mobilisation of the host sediment by fluid movement generated during magma fragmentation and rapid cooling. This process of sediment fluidisation can be understood by considering a bed of particles subjected to an upward flow of fluid. As the flow is progressively increased, a point is reached when the hydrodynamic drag force on the particles balances their weight, when the system is said to be incipiently fluidised. A fluidised bed behaves as a liquid; in the context of peperite generation this means that the clasts can move relatively freely through the host sediment.

Kokelaar (1982) identified two types of fluidisation in the context of the fluidisation of wet sediments during peperite formation: 'large volume' and 'small volume'. Large volume fluidisation occurs during the prolonged heating and convection of pore water that is driven by heat loss from the cooling intrusion. This results in the destruction of the original sedimentary structures in the sediment matrix of a peperite. The constant grain motion can also cause a progressive reduction in sediment particle size by attrition (Gravina *et al.* 2004); and this may account for the observation in some studies (e.g. Goto and McPhie 1996) that the sediment in a peperite is finer grained than in the undisturbed host sediment. Small volume fluidisation is short-lived and occurs during the local reduction in pressure associated with the opening of fractures. This results in local acceleration of pore fluid and the rapid fluidisation and transport of sediment into the fracture. This mechanism of transient pressure reduction, together with the fluidised transport and emplacement of sediments in fractures, was first clearly articulated by Walton and O'Sullivan (1950).

3 Characteristics of peperites

(i) Characteristics of juvenile clasts

Peperite breccias are monomict: all clasts have the same mineralogy and composition, which matches that of the parent igneous body. Peperite clasts are variably vesicular and can range in size from metres to centimetres and smaller. Clast shape includes the blocky and fluidal end members; however, in reality, clast shape

Figure 4 Jigsaw-fit of andesite clasts in a peperite in Hopper Quarry, Honister.

is variable, even within a given peperite. Skilling *et al.* (2002) list a range of other clast shapes including platy, tapered and ragged.

Several studies (e.g. Goto and McPhie 1996; Brown and Bell 2007) describe chilled margins on clasts in peperites. Chilled margins may be difficult to observe in older peperites, where the glassy texture has devitrified. However, some studies (e.g. Brown and Bell 2007) report that hydrothermal alteration of clasts has accentuated the chilled margins. If the presence of chilled margins can be established, it provides evidence that the clasts were molten on fragmentation and that the surfaces formed were quenched rapidly.

(ii) Characteristics of host sediments

Peperites have been reported in a wide range of host sediment compositions, particularly volcaniclastics. Sediment grain size varies from pebbles to clay, with varying degrees of sorting: these properties control the porosity, permeability and cohesiveness of the host sediment and thus the nature of the peperite produced. The sediments in close proximity to the peperite clasts show a range of features that attest to the contact of hot magma with wet, unconsolidated sediment.

Most studies (e.g. Goto and McPhie 1996) report that the original sedimentary structures in the host sediment have been destroyed adjacent to the peperite clasts. Some studies report bedding deformed around clasts (e.g. Branney and Suthren 1988). In all cases disturbance of the original sedimentary bedding by the peperite-forming process, indicates that the sediments were poorly consolidated at the time (Fig. 5, *oppopsite*).

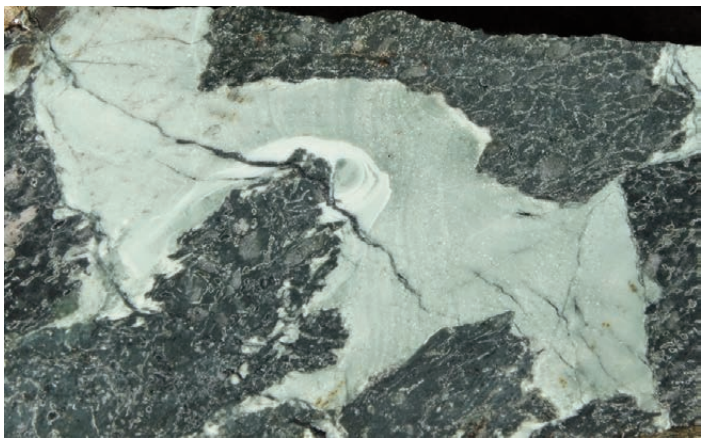

Figure 5 Sliced and polished sample of a peperite from Tuffen's Quarry, Honister, showing disruption of the host volcaniclastic sediment around a ragged andesite clast (field of view 20mm ¥ 30mm).

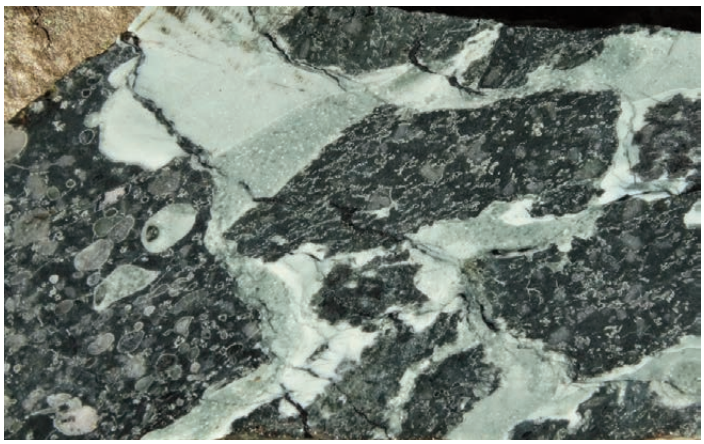

Figure 6 Sliced and polished sample of a peperite from Tuffen's Quarry, Honister, showing angular, 'ragged' andesite clasts, including one clast (left hand side) with a sediment-infilled vesicle (field of view 40mm ¥ 60mm).

Fine-grained sedimentary material is often found in vesicles (Fig. 6) and narrow fractures within the peperite clasts (Fig. 7), and within vesicles and fractures in the parent intrusion (Dadd and Van Wagoner 2002; Skilling *et al.* 2002). Such sediment infills are evidence of high mobility of the host sediment when fluidised by moving pore fluids.

The host sediment within the peperite may contain vesicles, now infilled with quartz, calcite or chlorite (Dadd and Van Wagoner 2002; Brown and Bell 2007). These vesicles are not present in the host sediment away from the peperite, suggesting that they are produced by the peperite-forming process. They are interpreted as vapour bubbles produced by boiling of pore water (Hunns and McPhie 1999). If present, they provide key evidence that the sediment was unconsolidated when in contact with hot clasts.

(iii) Summary

In general, peperites display a set of characteristics that result from their formation by *in situ* disintegration of magma by interaction with unconsolidated, typically wet sediments. Figure 8 *(overleaf)* attempts to summarise these characteristics; however, any given peperite may display only a subset of these characteristics.

*Figure 7 A large clast of andesite (*c. *300mm) in Hopper Quarry, Honister, with a fracture that is filled by fine grained slate, attesting to the highly mobile nature of the fluidised sediment during peperite formation.*

4 Peperites vs other sediment-matrix igneous breccias

'Peperite' is a genetic term; its use to describe a breccia presupposes that we can confidently assert that its formation was by the interaction of magma with wet, unconsolidated sediment. However, in the field, we are confronted by a monomict igneous breccia in a sediment matrix which could have originated in one of a variety of ways. In general, McPhie *et al.* (1993) recommend using a descriptive (non-genetic) name when initially confronted with a volcanic rock. Thus, a potential peperite might be described as a 'sediment-matrix igneous breccia' until its mode of genesis can be established. Several authors (e.g. Hunns and McPhie 1999; Brown and Bell 2007) use the method of multiple hypotheses (Chamberlin 1897) to list as many origins as possible for a given deposit and then to examine each hypothesis in the light of the field evidence before deciding on the most probable origin. In this regard it is critically important to keep a clear separation of description from interpretation when examining and interpreting field evidence. Finally, McPhie *et al.* (1993) state that, "Components, textures and structures are inherent properties of volcanic deposits and provide the basis for descriptive nomenclature; some give tight constraints on genetic interpretation but many merely suggest a number of equally valid alternatives".

As well as peperites, Rosa *et al.* (2016) describe four other types of sediment-matrix igneous breccias in the context of their study of such breccias in the Iberian Pyrite Belt. These are listed in Table 1 *(overleaf)* and discussed further below; between them they probably encompass most origins of sediment-matrix igneous breccias.

Sediment-infill volcanic breccias are the result of the deposition of sediment into the voids between mutually supporting clasts that are typically formed by autobrecciation as the cool, brittle upper surface of a lava flow is fractured by movement of the still-fluid interior. Sediment may subsequently enter spaces between the clasts by deposition from suspension as a geopetal infill. As well as indicating the paleohorizontal, the bedding or lamination in the sediments indicates that deposition of interstitial sediments occurred after the clast-forming process (Rawling *et al.* 1999). Such laminations will have the same attitude throughout the breccia, apart from local draping over clasts. Furthermore, the laminations should be parallel to bedding in the overlying sediments above the breccia.

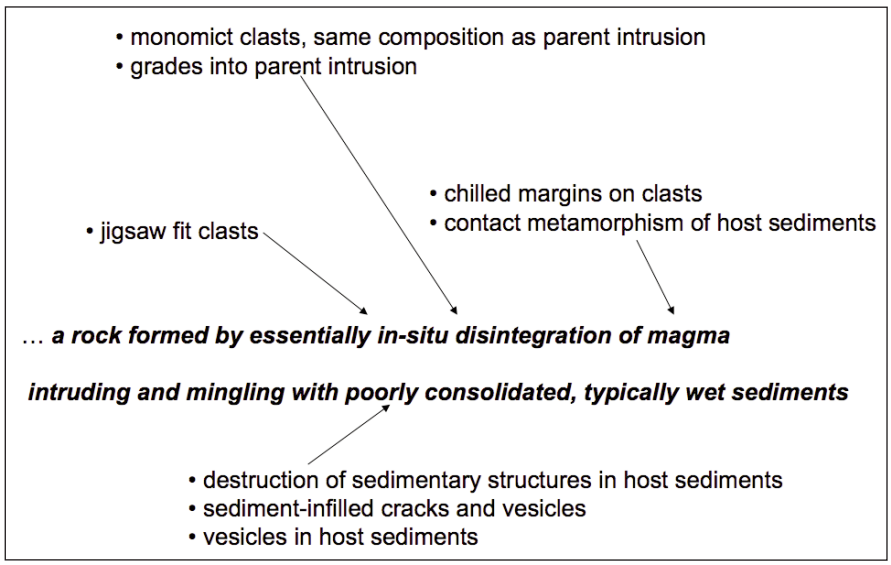
• monomict clasts, same composition as parent intrusion
• grades into parent intrusion
• chilled margins on clasts
• contact metamorphism of host sediments
• jigsaw fit clasts
… a rock formed by essentially in-situ disintegration of magma
intruding and mingling with poorly consolidated, typically wet sediments
• destruction of sedimentary structures in host sediments
• sediment-infilled cracks and vesicles
• vesicles in host sediments

Figure 8 A summary of the characteristics of peperites.

Mud-matrix resedimented hyaloclastites result from the collapse of a brecciated carapace on a subaqueous volcanic edifice and the generation of a density current, followed by transport of the clasts across muddy, unconsolidated sediment, which is progressively incorporated into the density current. Such breccias may show evidence of transport, so they would not, for example, display the jigsaw-fit texture that results from *in situ* fragmentation during the formation of a peperite.

Mud-rich water-settled fiamme breccias are the result of the explosive eruption of felsic magmas to produce pumice clasts that are deposited on water, become progressively waterlogged, and then sink and settle into fine-grained pelagic sediments.

Apparent sediment-matrix igneous breccias are produced by selective hydrothermal alteration of an igneous body (McPhee *et al.* 1993). The resulting contrast in the degree of alteration gives the appearance of a sediment-matrix igneous breccia, although the presence of relict phenocrysts in the more heavily altered 'matrix' could demonstrate its wholly igneous origin.

While it may be possible to assign a genetic name in a well-exposed and extensive outcrop at a locality where the rocks are unaltered and undeformed, Rosa *et al.* (2016) demonstrate some of the difficulties met with in the deformed and metamorphosed Iberian Pyrite Belt. This locality is an important volcanogenic massive sulphide (VMS) mining area. Since VMS deposits are emplaced on the sea floor, the ability to distinguish a breccia formed on the sea floor from a peperite formed on the margin of an intrusion, or from an apparent sediment-matrix igneous breccia, is important during prospecting for new VMS deposits.

5 Sheet-like igneous bodies: sills or lava flows?

In the field, we are sometimes confronted by a sheet-like igneous body within a sequence of sediments. Such sheets could have an intrusive or an extrusive origin. Furthermore, both sills and lava flows can have a sediment-matrix igneous breccia on the top margin of the sheet. The intrusive origin of the sheet can be established if the breccia can be demonstrated to be a peperite, rather than the brecciated top of a lava flow subsequently buried by sediment. As well as the economic importance discussed above, this distinction is important for understanding the chronological sequence of a series of igneous sheet, particularly when studying the chemical evolution of the magma that sourced the sheets.

Branney and Suthren (1988) studied a number of andesite sheets in the Lower Borrowdale Volcanic Group (BVG) of the Lake District. They showed that several sheets previously identified as blocky lava flows had peperites developed on the upper contacts and were thus intrusive, high-level sills rather than lava flows. Their study included the peperite exposures in slate quarries around Honister, which are described in the following section.

6 Peperite exposures around Honister

Peperites that developed on the tops and bottoms of andesite sills are well exposed in disused slate quarries on Fleetwith Pike above Honister Pass, Cumbria. These sills were emplaced into wet, unconsolidated volcaniclastic sediments produced by subaqueous reworking of pyroclastic fall deposits. Slaty cleavage developed in the sediments during the Acadian Orogeny (Woodcock and Soper 2006) and the resulting green 'Westmorland Slate' is still produced from the slate mines at

Table 1 Types sediment-matrix igneous breccias described in Rosa *et al.* (2016)

genetic description	*origin/formation*
peperite	*in situ* disintegration of magma interacting and mingling with unconsolidated, wet sediment
sediment-infill volcanic breccia	infiltration of sediment into the interstices of framework-supported igneous clasts
mud-matrix resedimented hyaloclastite	collapse of brecciated surface of a subaqueous volcanic edifice with incorporation of unconsolidated muddy substrate during transport
mud-rich water-settled fiamme breccia	settling of waterlogged pumice clasts into fine-grained pelagic sediments
apparent sediment-matrix igneous breccia	selective alteration of an igneous body

Figure 9 View of the centre of the main face at Hopper Quarry, Honister, showing the extensive white slickensided surface above the slate below. The peperite layer is just above the level of the debris on the quarry floor but is not clearly visible in this picture.

Honister. The resulting sequence of slates and sills comprises the Eagle Crag Member of the Birker Fell Formation. This formation comprises the early, pre-caldera, phase of the Borrowdale Volcanic Group and contains both andesite sills and lava flows.

The disused slate quarries can be reached from the Honister Slate Mine buildings and car park by walking up the track to a large, disused quarry (Hopper Quarry) at NY 213 138. Much of the upper face in the centre of Hopper Quarry comprises a white slickensided fault surface which displays prominent lineations or slickenlines (Fig. 9). The lower part of the face displays an irregular layer of clasts of variably vesicular material in a matrix of slate (Fig. 10). These are peperites that developed at the top of an andesite sill when it was intruded into the wet, unconsolidated volcaniclastic sediment. The smaller (20–50mm) clasts tend to be angular, while some of the larger clasts have more rounded outlines. The top of the peperite layer is irregular and gradational into the overlying host sediment. Overall, the clasts lower down in the layer are clast-supported; clasts become more widely separated higher up, with some clasts floating in a slaty matrix (Fig. 10). Such a matrix-supported texture could not develop in the brecciated top of a lava flow, where clasts must be mutually supporting. I speculate that such matrix-supported clasts might have vesiculated sufficiently to become buoyant. Donaire *et al.* (2002) describe a matrix-supported fluidal peperite that developed on the upper surface of a vesicular rhyolitic sill. They considered that the upper surface vesiculated to the point that the magma was less dense than the overlying host sediment. The resulting Rayleigh-Taylor instability promoted the detachment of globular clasts from the surface of the sill. Figure 7 shows a large clast of andesite with a fracture that is filled by fine grained slate, attesting to the highly mobile nature of the fluidised sediment during peperite formation.

Figure 10 A detailed view of part of the peperite layer in Hopper Quarry, Honister (field of view 1.5m ¥ 1m). The clasts lower down in the layer are clast-supported, but become more widely separated higher up, with some clasts appearing to float in a slaty matrix.

The top of the sill immediately below the peperite layer is not currently exposed in Hopper Quarry; however, a subsidiary quarry at NY 212 139 exposes an andesite sheet *c*. 10m thick that allows examination of its base (Fig. 11), where the peperitic margin is much thinner, and the clasts smaller and more angular than in Hopper Quarry (Fig. 12, *opposite*). The exposure in this quarry is described by Tuffen (2008), so I refer to this quarry informally as 'Tuffen's Quarry'. The base of the sheet shown in Figure 11 can be followed round to the left, where it trends uphill, immediately above the scree of quarry debris. The top of the sheet can be examined in scattered exposures, which show a range of peperite features. The sheet can thus be identified as a sill. The exposure in Tuffen's Quarry displays a wealth of features. As an example, Figure 13 *(opposite)* shows sediment-infilled vesicles within a ragged andesite clast, again attesting to sediment mobility while fluidised during peperite formation. Figsures 5 and 6 also show material from Tuffen' s Quarry.

Figure 14 *(opposite)* is a map of the area adjacent to the two quarries described above. Away from the quarries, exposure is patchy; however, the peperitic top of the sill exposed in Tuffen's Quarry can be examined at several locations. Figure 15 *(page 14)* shows a cross-section along the line AB on Figure 14. It is clear from the mapped outcrop and the measured dip of the sill in Tuffen's Quarry that the two quarry exposures of peperite relate to two different sills, which are part of a series of andesite sills emplaced into the slate precursor sediments. Figure 16 *(page 14)* shows several of these sills exposed on Fleetwith Pike immediately north-west of the slate quarries.

In Hopper Quarry, the peperitic upper margin of a sill is irregular; in contrast, the peperite-sediment interface on the lower margin of the sill in Tuffen's Quarry is remarkably sharp. I speculate that, on the lower margin of this sill, free convection within the wet sediment was suppressed. Heat loss from the lower margin was thus primarily by conduction and the sharp interface may represent the local boiling point isotherm at its maximum distance from the sill.

Acknowledgements

I am grateful to Drs Hugh Tuffen, Jennie Gilbert and Steve Lane (Lancaster University) for stimulating discussions in the field at Honister. Many thanks to Professor Chris Wilson (OU), who led a splendid OUGS NW Branch field trip in July 2019 to Honister and Haystacks.

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Figure 11 The main face of Tuffen's Quarry, Honister, is orientated ENE–WSW and shows a peperitic margin, about one metre thick, above slaty host sediments which dip diagonally to the right. The peperite has developed at the base of an andesite sill, c. *10m thick, which can be seen on the upper RHS.*

Figure 12 A detailed view of the peperitic margin at Tuffen's Quarry, Honister. The clasts are angular, variably vesicular and surrounded by a light bluish-grey sediment matrix.

Figure 13 Close up view of a group of clasts in Tuffen's Quarry, Honister. The central clast is angular, with a ragged margin, and is surrounded by the sediment matrix. Some of the vesicles in the clast are filled with the same sediment.

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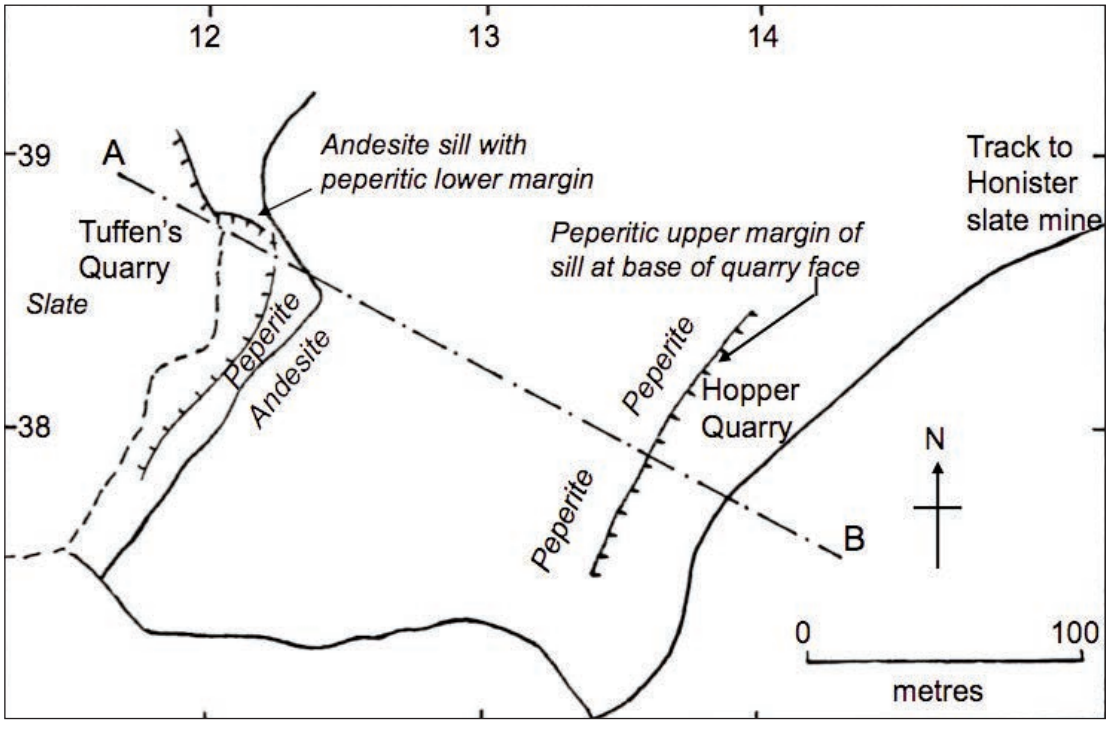
Figure 14 A map of the area around Tuffen's Quarry and Hopper Quarry, Honister, The line AB is the line of the cross section shown in Figure 15.



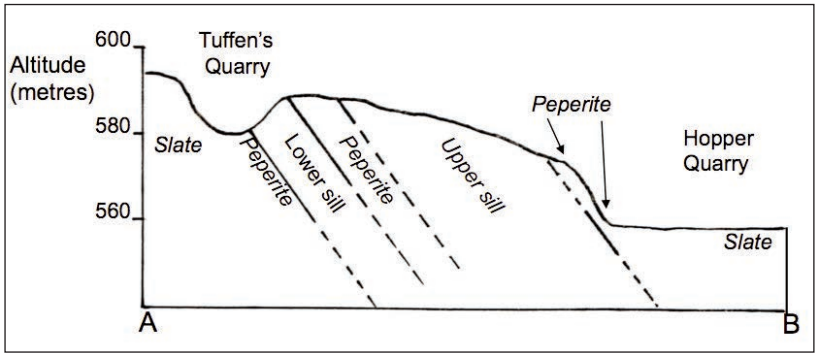


Figure 15 Cross section along line AB on Figure 15 (vertical exaggeration ¥2). The line of section is oblique to the dip direction of the base of the lower sill exposed in Tuffen's Quarry, where it dips at 39° to 152°. The orientation of the upper sill cannot be determined in the field but is drawn parallel to the lower sill.

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Figure 16 A series of andesite sills, with sub-parallel strikes, exposed on the south side of Fleetwith Pike, Honister. The slate dumps at Hopper Quarry, together with Tuffen's Quarry, can just be seen on the horizon at the far RHS. Photo taken from the Haystacks footpath at NY 205132, view north, with Little Round Howe in the foreground.

The formation of columnar basalt

Bob Mehew

Figure 1 Columnar basalt on south coast of Staffa, showing lower colonnades above an ash layer, and the ill-defined entablature and wavy upper colonnades.

Introduction

My interest in columnar basalt arose from a visit to Staffa to see Fingal's Cave many years ago, which led me to enquire into how columnar basalt was formed. Before describing the process of columnar formation, it is worth identifying some terminology describing columnar basalt, as defined by Long and Wood (1986).

(This brief article is a write-up of a short lecture delivered at the Northwest Branch AGM in February 2020. Figures are by the author unless otherwise indicated.)

Columnar formation

Figure 1 shows a view looking east, from above MacKinnon's Cave, located at the western end of Staffa's south coast. Above a series of ash layers making a platform covered by high tide, is the lower colonnade, clearly visible with its large almost vertically straight columns. The ash beds generally dip at about four degrees easterly from subsequent earth movement. Directly above the columns is an ill-defined zone of basalt, hinting at, but not clearly showing, a columnar structure called the entablature. There is a reasonably clear boundary between the lower colonnades and the entablature. Above the entablature is another zone, known as the upper colonnades, evident by the set of wavy columns in the upper mid part of Figure 1. The boundary between the top of the entablature and the wavy upper colonnade is reasonably defined in places in the photograph, but elsewhere is obscured by the angle of the view with respect to the cliff.

The formation of columnar basalt starts with a liquid lava flow. To keep matters simple, let us assume we had a flat horizontal land surface, over which the molten lava flowed and stopped with a flat top surface. (We shall ignore the edges.) At above 1,000˚ C, the lava starts to cool and energy in the form of heat is lost not only into the atmosphere above, but also into the ground beneath. As the lava cools, so the temperature drops. When the liquid lava becomes cool enough it solidifies. Thus, the process of columnar formation is a slow development from the bottom and top surfaces inwards towards each other over time (Fig. 2, *overleaf*).

With flat ground and air surfaces, the temperature profile mimics the flat surfaces and if measured, two flat, horizontal planes are found, which are parallel to the ground and air surfaces and have the same temperature. The rate of cooling depends on many factors, one of which is the supply of water. Water is known to penetrate between the solid columns, either under gravity from the surface or by upward pressure from

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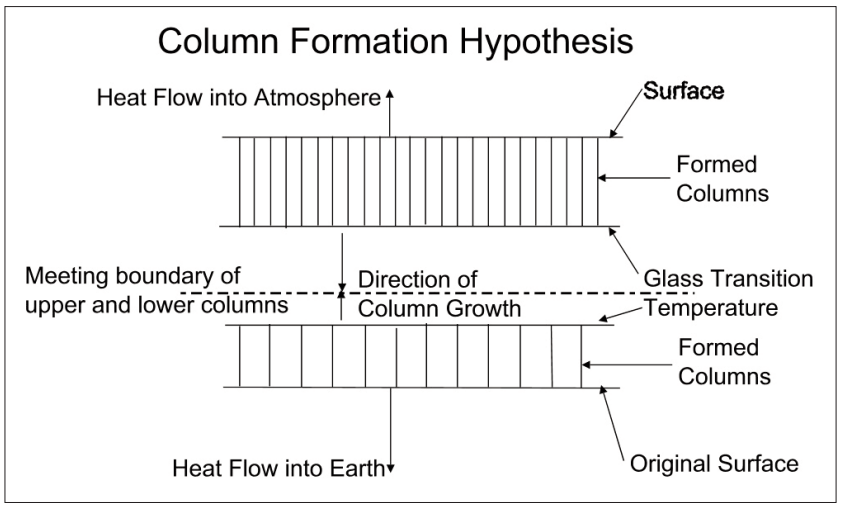


Figure 2 A diagram of the mode of columnar formation.

the ground. At a certain point, there is sufficient energy from the hot, but now solid basalt, to boil the water, and the steam escapes. This process is considered to be the main driver for heat removal and as one might expect the rate of extraction is dependent upon the amount of water available. Farther into the hotter zone of the solid basalt and then liquid lava, heat is driven by conduction. The rate of heat loss is considered inversely related to the cross-sectional size of the columns, so a slower rate of cooling creates bigger columns.

In our simple example, the flat horizontal temperature planes mean that the columns formed are at right angles to the two surfaces — top and bottom. This is a simple example, and many readers might ask, "What about curvy columns, such as those by Clamshell Cave on Staffa?" that greet you when you land on Staffa at the concrete jetty (Fig. 3). The answer is that there was not a flat land surface, so the temperature plane followed the shape of the land surface. This is strikingly demonstrated by MacCulloch's fossil tree on the western side of Mull, which stands some 12m high and has a 2m diameter (Fig. 4, *opposite*). The fossil tree was engulfed by a lava flow, but was large enough and with a fire-resistant bark (rather like the giant Sequoia redwoods) to withstand the molten lava coming into contact with the bark. As a consequence, the tree trunk formed a cylindrical cooling surface, and in Figure 4 short lengths of horizontal columns near the top half of the tree fossil can be seen. It is even more dramatically shown in a cross-sectional exposure in the nearby inter-tidal zone, which shows the columns radiating away from the fossil tree (Fig. 5, *opposite*).

Figure 6 *(opposite)* focuses on the polygonal nature of column formation, best shown in the classic cross-sectional exposure of the Giant's Causeway. I show this location because up until at least 2005, it was the only location in the world where someone had actually measured the cross-sectional nature of a sample of columns.

Figure 3 Curvy columns by the entrance to Clamshell cave.

Figure 4 MacCulloch's fossil tree in western Mull.

Figure 5 Cross-sectional exposure of another fossil tree on Mull, in the nearby inter-tidal zone, Mull.

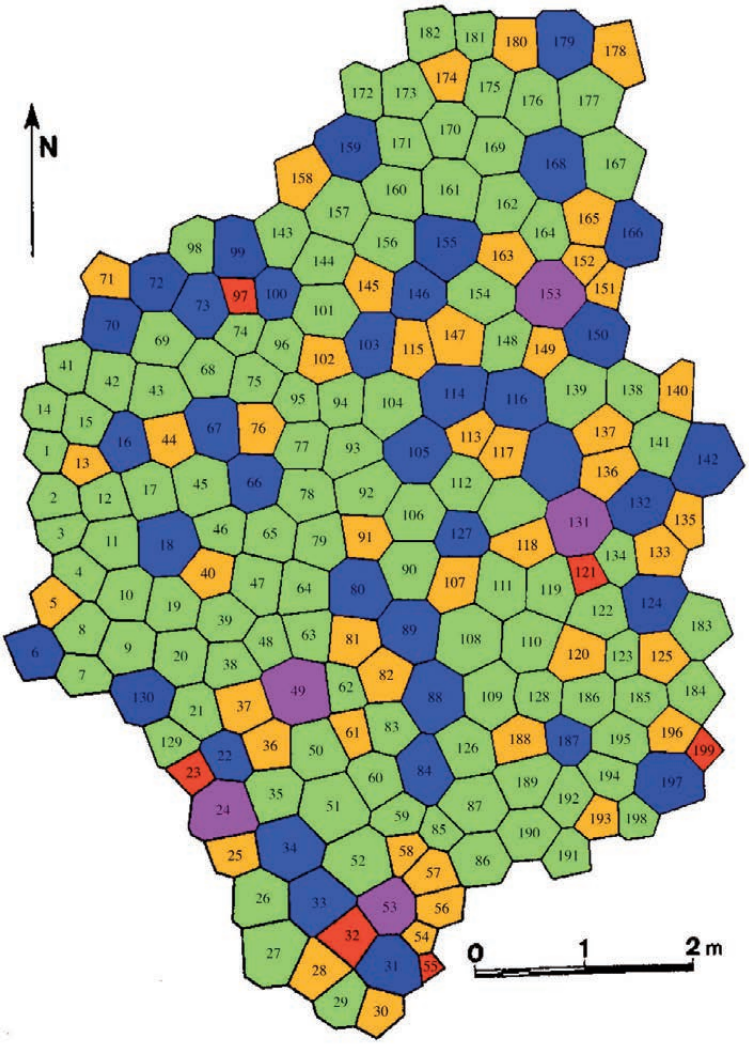
Figure 6 Columns at the Giant's Causeway in Northern Ireland.

The detail by Prof. O'Reilly was published in 1878, based on his work over three summers (O'Reilly 1879). He took measurements of the lengths of the sides and of their inter-side angles for some 200 column cross sections. His data have been re-presented in Figure 7 using different colours to represent different-sided polygons.

The red-coloured polygons are four-sided, orange are five-sided, green are six-sided, blue are seven-sided and mauve are eight-sided. The frequency of each type is plotted in Figure 8, which shows that six-sided polygons are the most prevalent.

Like most liquids, when lava cools it becomes more dense and thus shrinks in size. It also shrinks further when it solidifies (or more strictly speaking, transforms into a glassy structure). A good example of this is the recent work carried out by Wittmann *et al.* (2017). Using interferometric analyses of satellite-acquired synthetic aperture radar images they observed both subsidence due to phase change calculated analytically and subsidence due to thermal contraction. When lava solidifies, the contraction requires the development of surfaces that fill the absent spaces created by lava shrinkage. The creation of a surface takes energy (akin to the property of surface tension) and the hypothesis is that the solidified lava will form a polygon with a number of sides that equal the minimum perimeter length to polygon area ratio, which appears most frequently to be a hexagon.

Figure 7 Colour version (by author) of one of O'Reilly's plan views of columnar structure at the Giant's Causeway.



When they freeze or boil many liquids go through a super-cooling or super-heating phase in which the liquid remains liquid despite having passed the freezing or boiling point temperature. The postulate is that something similar occurs with cooling lava. Figure 9 *(opposite)* is a close-up of a lower colonnade in which two 'striae' (as used in Ryan and Sammis 1978) are highlighted by the yellow arrows. The conjecture is that at some point in time the lava has cooled such that the lower stria represents the border between solid basalt and lava. The lava continues to super cool until it solidifies ('freezes'). The sudden solidification occurs over a small depth, in this case some 90mm, and creates the higher stria. This phenomenon repeats itself over considerable distances, as can be seen in Figure 10 *(opposite)*, where some striae are highlighted by chalk marks. Indeed, the conjecture suggests that eventually, as the cooling process from above and below comes together, there is a final sudden solidification of the remaining lava to produce the entablature, as can be seen in Figure 1.

Acknowledgements

I am grateful to Prof. Stephen Morris (*see* Fig. 6) and to Prof. Lucas Goehring (*see* Fig. 11) for their help in educating me in the formation of columnar basalt. For more information on the physics of the processes involved, see:

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Figure 8 Frequency of polygon sides at the Giant's Causeway.

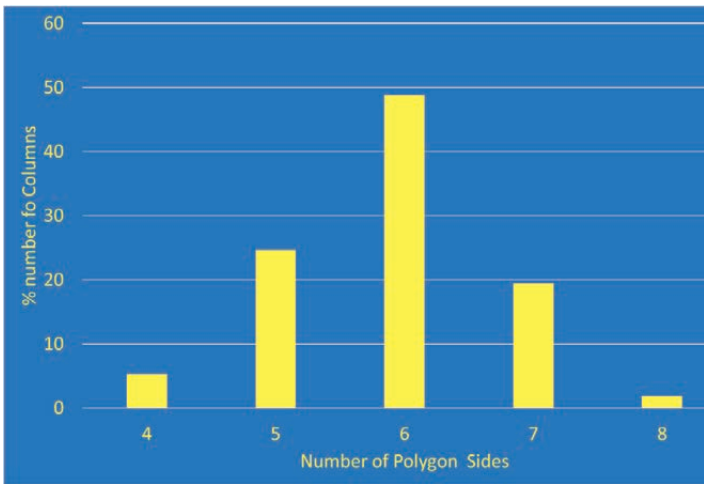
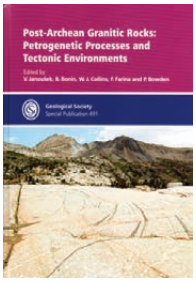


Figure 9 Close up of a lower colonnade near Fingal's Cave, Staffa showing striae highlighted by yellow arrows (© L. Goehring, reproduced with permission).

Figure 10 Columns showing horizontal striae near Fingal's Cave, Staffa.

Book revies



Janousek, V., Bonin, B., Collins, W. J., Farina, F., and Bowden, P. (eds) 2020 *Post-Archean Granitic Rocks: Petrogenetic Processes and Tectonic Environments*. London: Geological Society Special Publication 491 (ISBN 978-1-78620-448-6; 298pp; hardback £100)

Granitic rocks have a relatively simple mineralogy, but are produced by a range of processes, including fractional crystallisation of a more mafic magma (with or without assimilation of crustal rock) or partial melting of crustal rocks. This volume contains 10 contributions that address different aspects of granite petrogenesis.

The first paper provides a critical review of the various granite classification schemes that have been developed over the past 100 years or so. It demonstrates that no scheme is perfect, and that the debate on granite classification is likely to be ongoing. The 'S-I-A' petrogenetic classification of granites remains popular, despite its shortcomings, with four papers making extensive use of it. One of these papers looks in detail at A-type granites by comparing the classical anorogenic granites of the Nigerian ring complexes with A-type granites that occur in a sequence along with S- and I-type granites in the Lachlan belt of East Australia, suggesting a changing tectonic setting driven by subduction advance and retreat during an accretionary orogeny. Within the I-type (igneous) category, geochemically similar granites may be the product of fractionation of more mafic magma generated during subduction, or result from wet melting of pre-existing igneous rocks within the crust. Two papers deal with this complexity: one by means of thermal modelling, the other by the use of experimental petrology.

S-type granites are represented in the next paper, which provides an outstanding review of the petrogenesis of leucogranites in collisional orogens. Such granites are peraluminous, as characterised by the presence of muscovite and tourmaline, and are produced by partial melting of pelitic rocks during the crustal thickening, deformation and metamorphism that accompanies continental collision. This paper reviews their major and trace element geochemistry, isotopic indicators of source rock and age relations of a granite to the age of prograde metamorphism of its protolith. In addition, the paper reviews different melt generation mechanisms, favouring fluid generation by water-absent prograde reactions such as muscovite (and possibly biotite) dehydration rather than by the addition of externally derived fluids. Finally, it reviews potential heat sources within collisional orogens, concluding that a combination of radiogenic heat production and shear heating during crustal deformation can satisfy the heat requirements for melting.

Given adequate thermodynamic data, it is possible to calculate the phases in equilibrium at a given pressure and temperature for any bulk composition. Three papers concentrate on phase equilibrium modelling: one paper presents a new software tool, Rcrust, that automatically handles the changes in bulk composition that can occur during granite formation; the other two papers demonstrate the use of Rcrust to model melt extraction from a metapelite undergoing anatexis and to generate insights into the petrogenesis of a pluton in Sardinia.

The final paper continues the modelling theme by reviewing the current state of play for geochemical modelling of granite genesis. This contribution contains a clear overview of major and trace element modelling, together with the application of radiogenic isotopes. Under some conditions, some trace elements (e.g. Zr) form accessory minerals (e.g. zircon), and thus cannot then be modelled by the standard partition coefficient approach. This paper includes a detailed review of an alternative approach that involves the development of solubility models for accessory minerals in granitic melts. Finally, the authors review the links between geochemical modelling and phase equilibrium modelling, and anticipate new developments in this area.

This publication will interest anyone with an interest in granites and who has some prior knowledge, perhaps from a second- or third-level OU Earth Science course. Although the book is beautifully produced it is, perhaps, rather expensive at the list price; it is available at half price to Fellows of the Geological Society.

— Duncan Woodcock, MA (Cantab), BSc (Hons) (Open), PhD Continuing ES student

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Erratum

London Geological Society Memoir 50: *Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources* was reviewed by OUGS Memboir Stephen Crabtree in *OUGS Proceedings* 6, 2019, page 105. The editors of the memoir and the GS have sent the following erratum notice:

"The Editors would like to apologise for an error in the visualization of one of the map database codes, which resulted in the inclusion of some mafic intrusive rocks in the wrong age group in a number of figures.
The 15 revised figures for chapters 1, 3, 4, 6, 8, 11 and 22 can be download from: https://www.geolsoc.org.uk/m50-errata

— Editor

The major hyperthermal events of the Palaeogene: can hyperthermal events act as analogue models for present-day global warming and perturbations to Earth systems?

Ken Madrell

Introduction

I retired in 2013, having decided that I wanted to fulfil a lifelong desire to learn more about geology. I began my studies by following several L2 and L3 course with the Open University and by joining the Open University Geological Society (OUGS). Attending meetings and field trips organised by the OUGS enabled me to learn more about the landscape and its evolution from people who, like me, had a keen interest in the subject. In 2016 I enrolled in an online course at York University entitled 'The geology of Yorkshire and northern England', and it was while studying this course that I visited Whitby and learned about the effects of the Toarcian Oceanic Event (TOAE).

(This article is a summary and based on research that I completed in my OU studies.)

Ocean Anoxic Events

Schangler and Jenkyns (1976) described Oceanic Anoxic Events (OAEs) as episodes of widespread marine anoxia, during which large amounts of organic carbon were buried on the ocean floor under oxygen-deficient bottom waters. In the case of Whitby, the most extreme episode of this event was seen in the deposition of Whitby Jet, a finely laminated black bituminous shale, which is used to make ornaments and jewellery (Fig. 1).

Figure 1 The old jet workings at Saltwick Nab near Whitby. The dark strata in the centre of the photograph is Whitby Jet. It is the lowest layer of the Mulgrave Shale Member part of the Whitby Mudstone Formation (photo © A. McGrath, 2016)

The trigger for the TOAE is thought to have been volcanogenic and/or methanogenic sources, which caused a rapid release of carbon dioxide into the atmosphere resulting in global warming, a warming of the oceans and a fall in oxygen levels leading to the deposition of the dark shales.

The link between the environmental changes during the TOAE and present-day global warming has attracted many researchers. Often major warming events are associated with the release of large amounts of igneous material, which formed large igneous provinces (LIPs). In the case of the TOAE, the Karoo-Ferrar LIP was the likely source. An excellent book by Paul B. Wignall, *The Worst of Times* (2015), provides a detailed explanation of mass extinction events during the late Permian and Triassic periods. A further example of severe environmental disruption associated with igneous activity is the more recent Palaeocene-Eocene Thermal Maximum (PETM) *c.* 56Ma, which I studied in OU module S808 Earth science: a systems approach.

Fascinated by LIPs, mass extinction events, and OAEs and their environmental consequences I decided to explore this as my research topic for my OU Earth Science MSc project module (S810), which I submitted in September 2020. At the start of my research several months were spent during which I explored various aspects of OAEs and mass extinction events. My tutor guided me towards defining my research question and identifying a series of objectives that could be measured and evaluated through appropriate data.

Events before the Cenozoic, although well documented, did not provide me with the high-resolution data I required. The Ocean Drilling Programme (ODP) began in 1985. It has provided analyses of a number of marine sediment cores extracted by these programmes revealing that in the early-mid Palaeogene (65Ma to 40Ma) many global warming events occurred. The first and largest event was the Palaeocene–Eocene Thermal Maximum (PETM), identified by Kennett and Stott (1991) in their study of ODP Site 690 in the South Atlantic. ODP records show changes in temperature and the carbon cycle, and reveal a large number of short, rapid warming events termed hyperthermals.

Hyperthermals are described as intervals of rapid, pronounced global warming associated with negative excursions of oceanic $\delta^{13}C$ and with clay-rich layers indicative of reduced sedimentary calcium carbonate ($CaCO^3$), content commonly interpreted as a response to increased $CaCO^3$ dissolution. The hyperthermal events of the Palaeogene became the focus for my research.

I established four objectives to address the following issues:

(i) identifying the major hyperthermal events of the Palaeogene based on the criteria identified in the definition above;
(ii) using ODP data to measure and describe the magnitude, duration and shape of these events;
(iii) reviewing the cause of the events; and
(iv) describing the environmental consequences of the events.

My research identified more than 50 hyperthermal events, of which 10 events, including the PETM, met the criteria of a hyperthermal event as described above; and there was data and previous research available to enable an evaluation of these events.

For each event the ODP records were used to construct graphs showing the size of the event, its duration and shape. The PANGAEA database www.pangaea.de was the data source for the ODPs. The largest event, the PETM, was about five times the size of the other events. The magnitude of the events was measured by the negative excursion in the stable carbon isotope record ($\delta^{13}C$). While the PETM recoded a negative shift of *c.* –3‰, most other events registered smaller negative excursions between

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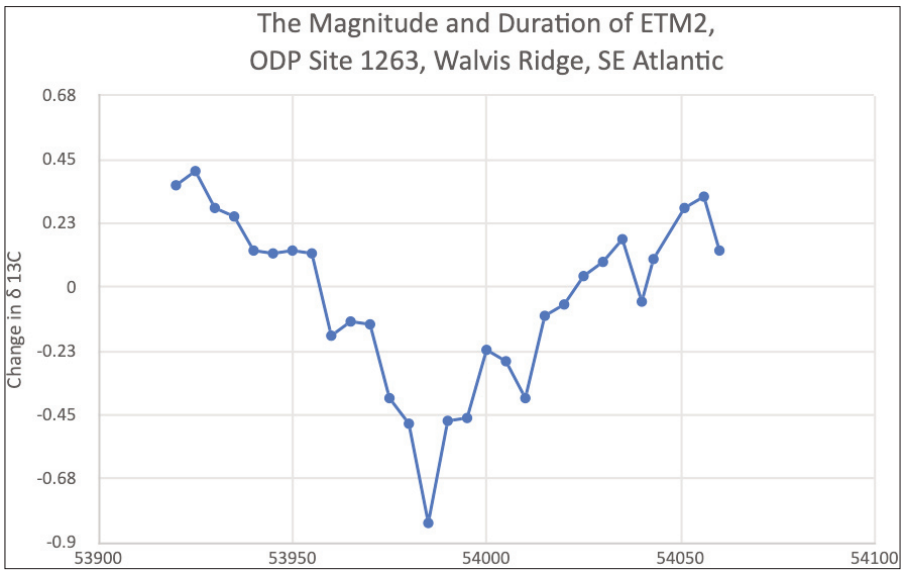

Figure 2 The magnitude and duration of ETM2, based on the benthic stable carbon isotope record from ODP Site 1263, Walvis Ridge, SE Atlantic (graph created in Excel from data set at PANGAEA.854818 — Benthic stable carbon isotope record for ODP 1263, Lauretano et al. *2015).*

–0.5‰ and –1.0‰. The events varied in duration from *c.* 50,000 to 200,000 years, and some had an asymmetrical shape while others had a more symmetrical appearance. The shape reflects how the carbon cycle was affected and responded to Earth system feedback mechanisms. Figure 2 illustrates the magnitude, duration and shape of Eocene Thermal Maximum 2 (ETM2), one of the major events studied in my research. This event had a broadly symmetrical shape and had a negative carbon excursion of –1.15‰. It was the second largest event of the Cenozoic.

A critical revciew of the literature was undertaken to examine the causes of the events. Although igneous activity related to the North Atlantic Igneous Province could have been associated with the largest event, the PETM, most of the other events appear to have been associated with changes in orbital cyclicity: when the Earth was closest to the Sun temperatures increased, the oceans and the land were warmed, causing the release of greenhouse gases that led to further warming.

Did an initial warming then trigger additional sources of carbon dioxide and methane from climate sensitive reservoirs? Today we are witnessing rapid anthropogenic warming, causing the melting of permafrost and the demise of peat bogs. Evidence from my research showed that during the Early Eocene Climatic Optimum (EECO) *c.* 53–49Ma, the events known as the Eocene Thermal Maximum 2 (ETM2), H2, I1-I2 and Eocene Thermal Maximum 3 (ETM3) were all triggered by changes in orbital cyclicity.

Lauretano *et al.* (2015) proposed that differences in the slopes of the regression lines measuring the relationship between $\delta^{13}C$ and $\delta^{18}C$ could indicate different sources of additional carbon. Table 1 illustrates that the statistical analysis of the paired events ETM2-H2 and I1-I2 shows that the regression lines of the secondary events (H2 and I2) had steeper slopes than the primary events (ETM2 and I1), indicating a different source of additional carbon. It is proposed that warming during the primary events released methane hydrates, but that as these became exhausted, further warming during the secondary events lead to the release of methane from other climate-sensitive reservoirs, such as peat lands and permafrost.

The events of the EECO demonstrate perturbations to the carbon cycle, arising from global warming passing a threshold value and impacting on the climate-sensitive carbon reservoirs in a similar manner to the present-day degradation of permafrost and rising levels of atmospheric carbon dioxide (pCO_2). Although the present-day anthropogenic warming is much more rapid, the events of the EECO nevertheless demonstrate the impact of rising global temperatures on the carbon cycle. It is argued that the different shapes of the events —symmetrical, asymmetrical and stepped — illustrate how the different feedback mechanisms restored the carbon cycle to equilibrium.

The different impact these events had on the marine environment is shown by comparing records for ocean warming, changes in ocean chemistry and changes to the marine life. Ocean warming is measured by negative excursions in $\delta^{18}C$. Figure 3 *(opposite)* illustrates the change in iron content (Fe) as a measure of carbonate dissolution during the Eocene Thermal Maximum 3 (ETM3) event. The higher the iron content the greater the rate of carbonate dissolution. Another measure to demonstrate changes in ocean chemistry is the changes in calcium carbonate content.

The changes in the marine environment caused by warmer waters, de-oxygenation and increasing acidity showed an overall decrease in benthic foraminifera and an increase in the abundance of radiolarians and warm-water planktic foraminiferal genera. Calcareous nannofossil assemblages of oligotrophic taxa decreased their abundance while eutrophic taxa increased their abundance. However, it is worth noting that there were no mass-extinction events in the marine environment, and that ocean acidification was a relatively short-lived phenomena (30k), as illustrated in Figure 3.

Table 1 The strength of the correlation between the carbon and oxygen isotope values and the angle of slope of the regression lines for the paired events of the EECO

name of event and date	*strength of correlation* R^2 =	*angle of slope*	*possible source of additional carbon*
ETM2 – H1 *c.* 53.7 Ma	0.8012	42°	methane hydrates
H2 *c.* 53.6 Ma	0.8365	58°	permafrost melting, wetlands and peats
I1 *c.* 53.4 Ma	0.7866	36°	methane hydrates
I2 *c.* 53.3 Ma	0.8604	50°	permafrost melting, wetlands and peats

Significantly, five of the ten events studied occurred during the four million-year-period of the EECO, when temperatures and levels of atmospheric carbon dioxide (pCO_2) reached a maximum. Today, global sea temperatures are increasing, especially in high latitudes. The Intergovernmental Panel of Climate Change (IPCC 2019) reports that in the Arctic Ocean between 1982 and 2017 temperatures increased *c*. –0.5˚C each decade. Lauretano *et al*. (2018) demonstrate that deep sea temperatures increased from *c*. 12˚C before ETM2 to 14°C during the EECO. These changes were also greater in high latitudes.

In November 2020, pCO_2 levels reached *c*. 442ppm, having increased from 283ppm in 1800. Greene *et al*. (2019) demonstrate that pCO_2 levels increased from *c*. 420ppm in 66Ma to a maximum of 1182ppm towards the end of the EECO. Research by Cui and Schubert (2018, 214) showed distinctive peaks in pCO_2 during the PETM, ETM2, H2 and I2 events.

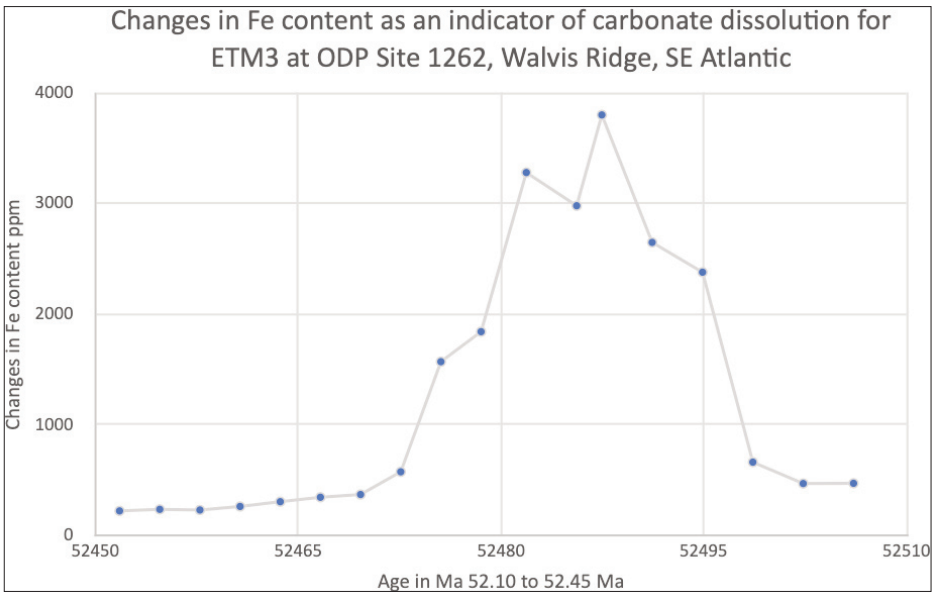

Figure 3 Changes in Fe content as an indicator of carbonate dissolution for the ETM3 at ODP Site 1262, Walvis Ridge, SE Atlantic (graph created in Excel from data set at PANGAEA.833209 — X-ray fluorescence (XRF) of iron (Fe) core scannings at ODP Site 1262, Littler et al. *2014).*

Although it is acknowledged that the rate of increase in CO_2 levels and anthropogenic warming is much more rapid than the events of the Cenozoic, nevertheless, I proposed that investigating these events, especially those of the EECO, could improve our understanding of how present-day global warming could impact on the carbon cycle and Earth systems. Events of the EECO can provide more realistic models than the larger PETM and other major global warming events of the Permian, Triassic, Jurassic and Cretaceous periods. Future research of the impacts on the terrestrial environment during these events would further increase our understanding of global warming and changes to Earth systems.

Further reading and references

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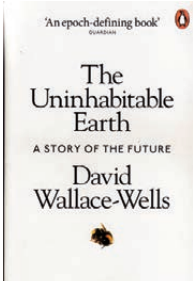
Book review



Wallace-Wells, David 2019 *The Uninhabitable Earth: A Story of the Future.* London: Penguin Random House (ISBN 978-0-141-98887-0; 320pp; paperback £9.99)

David Wallace-Wells is Deputy Editor of *New York* magazine, and a science and technology writer who frequently addresses issues of climate change and earth science technology.

His *Uninhabitable Earth* is a hard-hitting, serious, well documented, often depressing and often frightening read. Do not read this book lightly, but rather to learn and address the issues and to inform, elucidate and illuminate yourself.

Wallace-Wells backs up every statement he makes with his sources, so you can follow them up yourself. There are 67 pages of notes and references, printed in what appears to be about half the font size of the main text. He often gives 'alternative' interpretations of the data by others, but when he states facts, he states them unequivocally and without frills or hedging. He is an investigative reporter and reports what he finds.

This book is less (in minute detail), for example, "about the science of [global] warming; it is about what warming means to the way we live on this planet."

In a sentence this book is about what we humans have done and are doing to our climate and to the Earth, what the consequences are likely to be according to the best and most recent research and modelling, and what we *could* do about it if we choose to do so.

He does not mince his words about what has already been done, and what state our climate is in as of 2018–19. Nor is he either over- or under- pessimistic. Like the old TV show *Dragnet's* Sergeant Joe Friday, "All we want are the facts, ma'am".

Through the book, Wallace-Wells explains clearly where we are at now in terms of average global temperature, ocean temperature, carbon dioxide levels, increasing wildfire frequency worldwide, the spreads of plastics and what is the most likely outcome of our own actions by *c.* 2050. It is all documented meticulously and it is not a pretty picture.

Here is a second example. In the chapter 'Freshwater drain' Wallace-Wells discusses the global problem with providing safe water to the world's growing population. He describes a drought in Cape Town, South Africa in 2018, explaining that the city's government set a limit of 23 [US] gallons of water per person per day. Disturbingly, he then reports that the average American citizen "goes through four to five times that much"; that's 92 to 115 US gallons per person per day! Then, *horrifyingly*, he reports that, "in arid Utah ... the average citizen goes through, each day, 248 gallons"! (I read this sentence three times trying to make sense of it. I can only assume that in Utah there are a lot of farmers, and that this figure is an average per Utah citizen. Even so, if urban dwellers in Utah use less water per day, then farmers must use even more than this amount of water per day.) I have my Thames Water household records for 2015 to 2020. So, curious to compare my own water usage, I did the maths: I converted Thames Water's m^3 meter readings to litres, then litres to US gallons (1 litre = 0.26 US gallon), then the calculation for usage per day — *in our two-person household.* It is 60.2 US gallons per day; that is, on average 30.1 US gallons per person per day. I am *not* seeking a pat on the back, just stating the facts.

In the end, however, he is not a doomsayer. He also discusses what can be done, but overwhelmingly and persistently he advocates, even importunes, urgency; and exhorts global thinking and cooperation above all, and urges us to override national bunkering, finger-pointing, wait-and-see-ism — or crowing about 'what we've done already'.

David Wallace-Wells is not Greta Thunberg, whom he clearly admires and encourages. But he submitted his text to the publisher in September 2018. The United Nations had released its "Doomsday" report about the same time (Intergovernmental Panel on Climate Change [IPCC] 2018: *Global Warming of 1.5˚C: An IPCC Special Report on the Impacts of Global Warming of 1.5˚C Above Preindustrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty).* At that time, Greta Thunberg was as yet relatively unknown, at least outside Sweden. And, fact, by 2018, the data indicated that we had (or almost had) reached 1.5˚C, and in fact were more likely headed for 4˚C by 2050.

Regrettably, Wallace-Wells' 10-page index was not updated in 2019, when he wrote a 10-page 'Afterword to the Paperback Edition'. Thus, for future reference, you will need to add 'Thunberg, Greta, 231' to the index in your own copy (as I have).

Sadly, the COVID-19 pandemic has overtaken focus on climate change issues. And Greta Thunberg's initial impact as a rallying point is being manipulated by politicians and the media.

Read the book. Assess what *you* think. I'll bet you knew a lot less than you thought about these matters.

I certainly did!

— David M. Jones, OUGS Proceedings Editor

Ice and ocean: a look under Antarctic ice shelves

Sue Graham

Why are ice shelves important?

Antarctic ice shelves are the floating part of the Antarctic ice sheet, formed where grounded ice meets the Southern Ocean Some are vast, such as the mighty Ross ice shelf, the largest in the world (Fig. 1). They fringe most of the Antarctic continent, about 300 in total, extending the ice sheet by *c*. 13% and accounting for about 11% of the entire Antarctic ice mass. Much of their importance lies in the fact that they buttress the ice sheet, slowing the flow of the 30 or so major glaciers into the ocean (Fig. 2).

Loss of this stabilising effect due to ice shelf thinning causes accelerated ice flow from up to 900km inland, with corresponding global sea level rise. Unsurprisingly, many ice shelves are melting, and at an accelerating rate. Ensuing meltwater results in ocean freshening, which is the other major factor in their importance, as fresher water impedes the deep convection necessary to form Antarctic Bottom Water (AABW). AABW is the densest and most voluminous water mass in the global ocean, filling the abyssal layers of the three major ocean basins (Atlantic, Pacific, Indian) and forming the bottom limb of meridional overturning circulation (MOC). As such, it is a key component of global ocean circulation, regulating the cycling of heat, carbon and nutrients around the oceans (Lago and England 2019). Understanding ice shelf dynamics is therefore essential for predicting the future stability of the Antarctic ice sheet, global sea level rise, ocean circulation, global climate and ocean biogeochemistry in the 21st century and beyond.

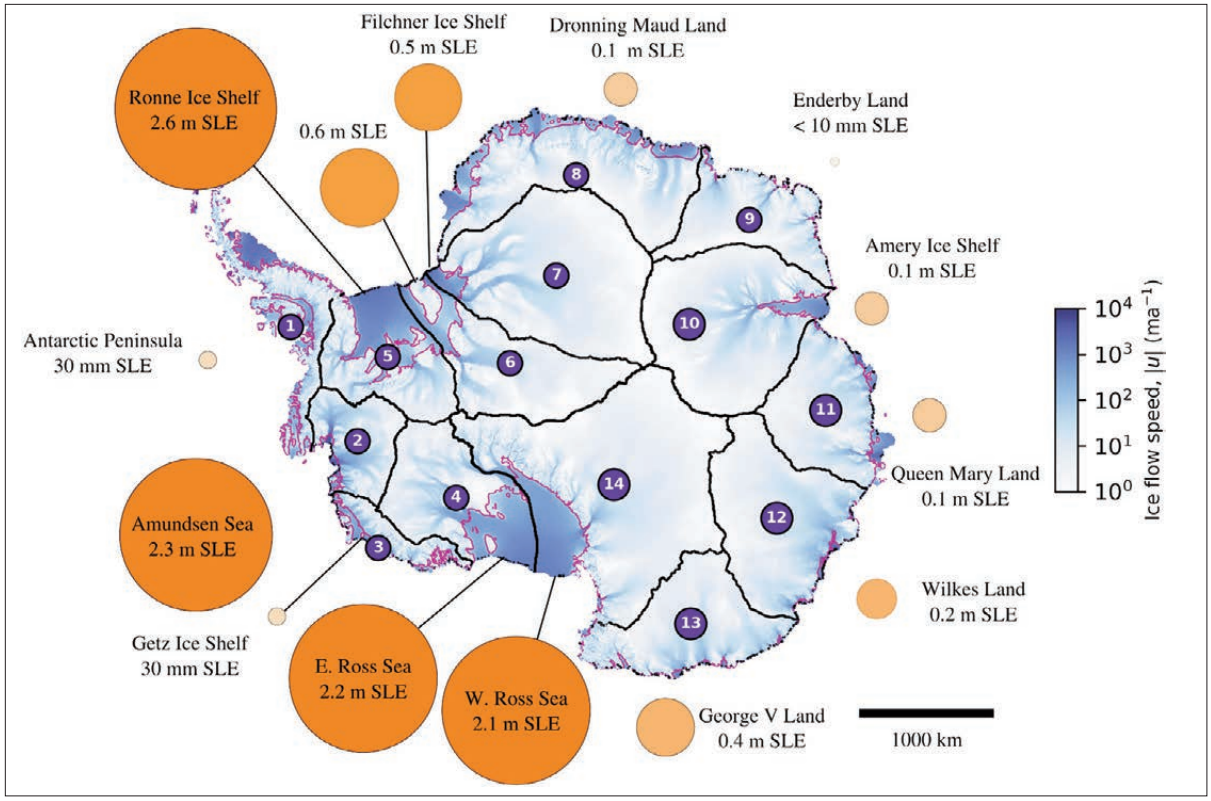
Ice shelf mass loss is caused by two processes: melting at the ice shelf base and iceberg calving at the ice shelf front. This article is concerned with basal melting, which is now known to be the larger contributor and the single largest cause of Antarctic ice sheet mass loss (Stewart *et al*. 2019).

Figure 1 Cliffs of the Ross ice shelf, Antarctica (see Holland et al. *2020).*

How the data is gathered

Observational data, both *in situ* and by satellite observation, and modelled simulations are used to investigate ice shelf–ocean dynamics and estimate basal melt rates. Investigations range from continent-wide surveys to the study of individual ice shelves. *In situ* oceanographic observations are made using autonomous submersibles and borehole instrumentation, instrumented elephant seals and mooring or ship-based observations beyond the ice shelf perimeters. However, *in situ* observations are scant or

Figure 2 The Antarctic continent, showing modelled ice flow speed in shaded blue. Ice shelf grounding lines are shown in magenta. Orange circles show eustatic sea level equivalent (SLE) after 1,000 years of extreme, sustained ice shelf thinning in the numbered sectors (after Martin et al. *2019).*



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non-existent in this inhospitable environment. Mooring and ship-based observations are mostly restricted to summer months when ship access is possible, while data from instrumented seals is limited to their diving range. Data collected by satellite laser and radar altimetry is therefore relied on, but spatial and temporal observations give incomplete coverage of a dynamic seascape/icescape. A variety of ocean circulation models simulate sub-ice shelf processes, but with the scarcity of observational data to constrain the models and a lack of knowledge of basic parameters — such as temporal variability, bathymetry and changing ice shelf geometry — there are significant discrepancies among model results. Furthermore, ice shelf–ocean interactions are not included in phase 5 of the Coupled Model Intercomparison Project (CMIP5) used for IPCC climate change projections, and therefore CMIP5 models have underestimated the effect of ice shelf and ice sheet meltwater in global projections of climate and ocean circulation change (Lago and England 2019). How long it will take for the ice shelves that are currently thinning to lose their buttressing effect is unclear, therefore the stability of the Antarctic ice sheet (AIS) and future impact of ice shelf and ice sheet meltwater fluxes on global sea level and ocean circulation remains uncertain.

Three water masses that interact with ice shelves

To understand why ice shelves are melting at their bases we need to look at the water masses that enter ice shelf cavities several hundred metres below sea level on the continental shelf. Because there are three distinct water masses (defined by temperature and salinity) that enter the cavities spatially and temporally, ice shelf basal melt rates vary widely around Antarctica.

Dense Shelf Water is formed on the continental shelf in winter, when seawater is cooled to the surface freezing point and sea ice is formed. Brine rejection, which accompanies sea ice formation, salinifies the water column. This very cold, very saline water mass is dense enough to sink to the seafloor. It cascades over the continental shelf break and down the continental slope into the abyssal ocean, forming Antarctic Bottom Water (Lago and England 2019).

Circumpolar Deep Water is the most voluminous and warmest water mass in the Southern Ocean. It flows clockwise around Antarctica in the Antarctic Circumpolar Current and spreads from offshore across the continental shelf, entering ice shelf cavities at *c*. 400–500m depth. With temperatures exceeding 0˚C, which is 2–3˚C above the freezing temperature at this depth (the freezing point depends on pressure), it is the most important heat source for ice shelf basal melting, incurring high melt rates.

Antarctic Surface Water is a comparatively fresh, warm water mass that forms due to solar heating and sea ice melt in summer. Being relatively buoyant, it is driven into shallow ice shelf cavities by tides and wind, where it can cause intense, seasonal melting (Stewart *et al.* 2019).

Three modes of basal melting

These three water masses, with their distinct heat contents, drive three modes of basal melting (Fig. 3):

Mode 1 is driven by Dense Shelf Water (DSW). Although very cold, it is warm enough to melt the base of deep ice shelves owing to the dependence on pressure of the freezing point of seawater, mentioned above. These ‘cold water’ ice shelves have relatively low area-averaged basal melt rates because of the limited supply of heat. Moreover, substantial refreezing occurs when a meltwater plume of Ice Shelf Water rises and super-cools, forming marine ice, which accretes to the ice shelf base at shallower depths and thus reduces net mass loss (Silvano *et al.* 2017).

Mode 2 is driven by relatively warm Circumpolar Deep Water (CDW) accessing the continental shelf from offshore and reaching ice shelf cavities. These ‘warm water’ ice shelves have the highest basal melt rates, *c.* 50% of which occur in the Amundsen-Bellingshausen Seas of West Antarctica, where the Antarctic Circumpolar Current, which transports CDW, is relatively near the shelf break (Silvano *et al.* 2016). As CDW crosses the continental shelf it is cooled by mixing with shelf water, forming modified CDW (mCDW).

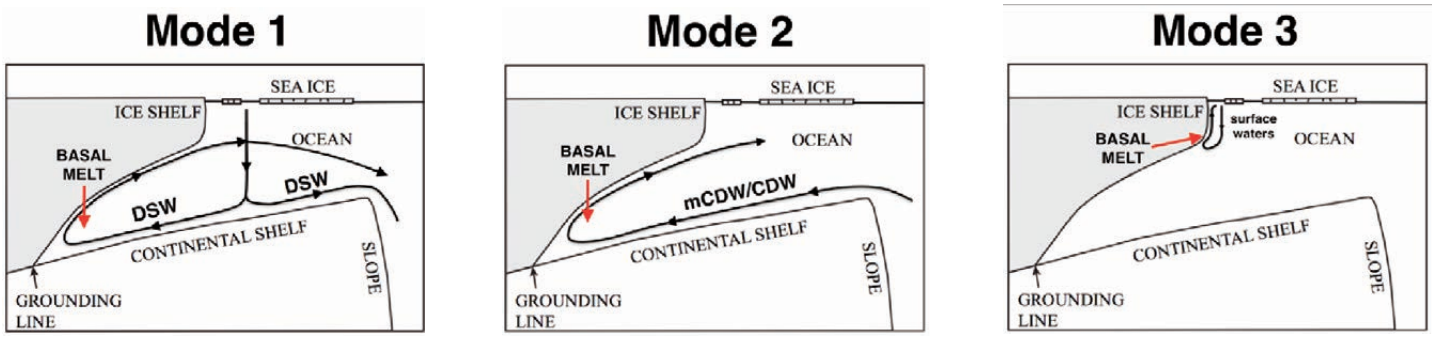
Of particular importance among these ‘warm water’ ice shelves in terms basal melt rate are the Pine Island and Thwaites in the Amundsen Sea, and the Totten ice shelf in East Antarctica.

Mode 3 is driven by Antarctic Surface Water, which is transported to ice shelf fronts and shallow-depth cavities by wind, tides, eddies and ocean currents. The heat content of Antarctic Surface Water is seasonal; it has a cold core of ‘Winter Water’ with a temperature near the surface freezing point, and a solar-warmed and fresher upper layer. Throughout most of the year, Mode 3 melt rates are similar to Mode 1 rates, but in summer basal melt rates increase significantly owing to solar heating of surface water (Lindbäck *et al.* 2019).

Other factors that enhance ice shelf basal melting

Retrograde bed slopes Most of the seabed around Antarctica is retrograde — sloping down towards the continental interior. The result is fast retreat at the grounding zone, which may initiate

Figure 3 Mode 1, Mode 2 and Mode 3 basal melting (images CC BY 4.0: after Silvano, A., Rintoul, S. R., and Herraiz-Borreguero, L. 2016 ‘Ocean–ice shelf interaction in East Antarctica’. Oceanogr ***29****, 130–43.*



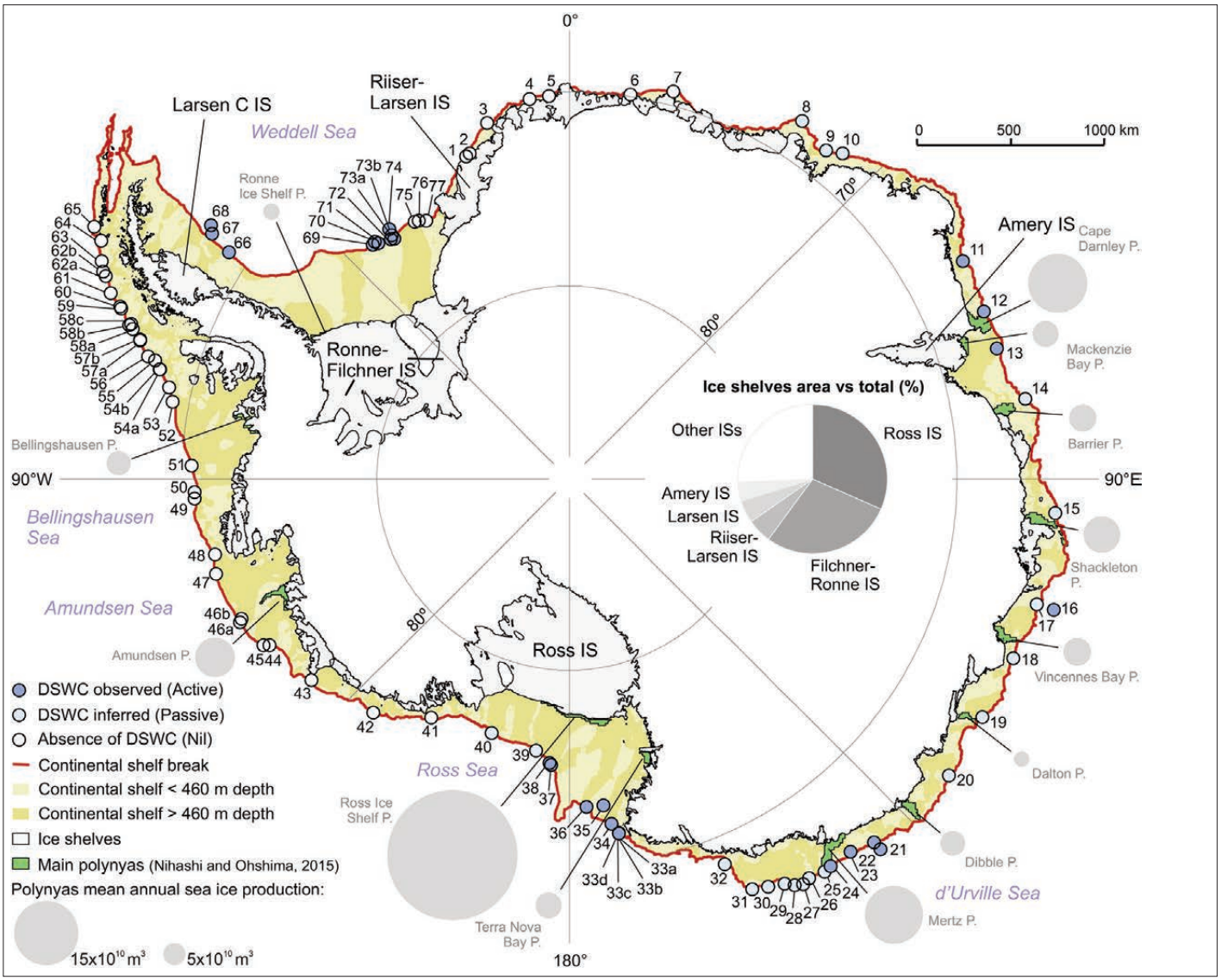
marine ice sheet instability (MISI) and possible runaway retreat (Scambos *et al.* 2017).

Bathymetric troughs, mostly carved by past glacial advances preferentially channel Circumpolar Deep Water across the continental shelf toward ice shelf cavities. The cavities are also often traversed by troughs, which can form quickly owing to CDW intrusion, particularly in the CDW-flooded Amundsen and Bellingshausen seas. Basal melting is enhanced in inner-cavity troughs near the grounding line, promoting deepening of basal troughs, loss of buttressing and ice shelf retreat. Cross-shelf troughs have a dual role, as they also act as drainage conduits for the transport of DSW to the shelf edge, where it then cascades to the abyssal ocean, forming AABW (Alley *et al.* 2019).

Coastal polynyas are areas of thin ice or open water in the winter sea ice cover, formed in spring by divergent ice motion owing to prevailing southerly winds and ocean currents. They are most 'active' in winter when sea ice formation is enhanced. 70–90% of salt is rejected from the ice during this process (Ohshima *et al.* 2016). These 'ice factories' produce cold (approximately surface freezing point) and saline (>34.5) DSW, which both reaches the deepest areas of ice shelf cavities, driving Mode 1 basal melting, and cascades down the slope, forming AABW. About 90% of the West Antarctic Ice Sheet (WAIS) drainage goes into the Ross, Weddell, and Amundsen seas (Turner *et al.* 2017). All three are in the proximity of active coastal polynyas.

There are 13 major active polynyas in Antarctica (Fig. 4). The strongest (in terms of sea ice production) are the Ross Ice Shelf polynya and the Weddell polynya. The Darnley polynya near the Amery ice shelf in East Antarctica has the third highest sea ice production. Not all polynyas produce DSW, however. Although the Dalton polynya on the Sabrina coast in East Antarctica, and the Amundsen polynya in the Amundsen Sea, produce a high volume of sea ice each year, (*c.* 50km^3 and 120km^3, respectively), no DSW is formed because year–round stratification of the water column is increased by basal meltwater from nearby ice shelves, inhibiting deep convection needed to produce DSW. Stratification prevents relatively warm (>0˚C) saline (>34.7g kg^{-1}) CDW on the continental shelf from losing its heat to the atmosphere and, in the absence of DSW, is able to reach ice shelf cavities, where it drives Mode 2 basal melt of 'warm cavity' ice shelves (Silvano *et al.* 2018).

Figure 4 Map showing ice shelves, coastal polynyas and DSW cascades: sizes of the grey circles are proportional to sea ice production of polynyas; numbers represent nearly 50 years of observations (after Amblas and Dowdeswell 2018; reproduced with permission from Springer Nature [fee waived] under Creative Commons Attribution 4.0 International License).



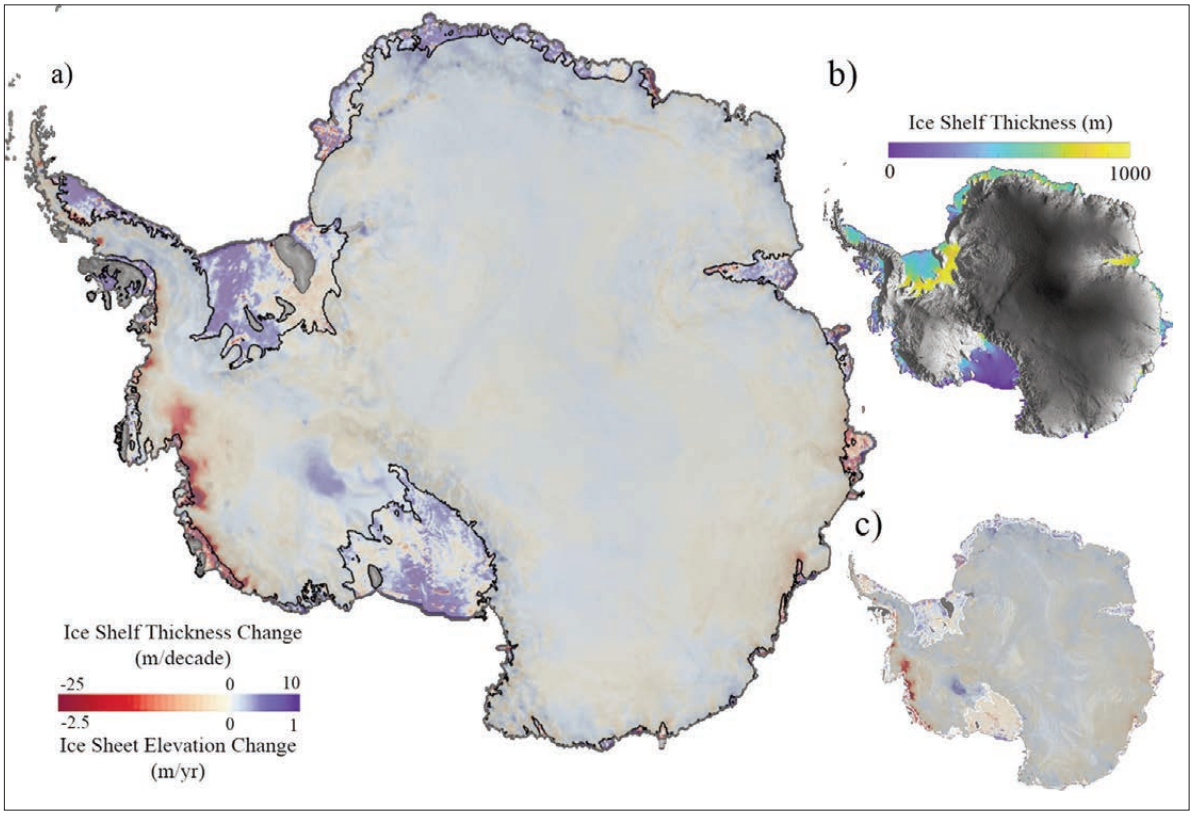


Figure 5 (a) Antarctic ice shelf thickness change measured by CryoSat-2 satellite radar altimetry 2010–2017. Black lines show ice shelf grounding lines; (b) map of the thickness of ice shelves; (c) 25 year rate of ice shelf thickness (after Hogg et al. *2020; CC BY 4.0)*

In summer, polynyas absorb solar heat rapidly and Antarctic Surface Water is formed, causing strong seasonal melting of ice shelf bases near ice front regions (Stewart *et al.* 2019). The coldest summer sea surface temperature (SST) is typically near the Antarctic coastline, as it is inversely correlated with sea ice concentration; but higher SSTs are found in coastal polynyas, with the Ross Sea and Cape Darnley polynyas near the Ross and Amery ice shelves having the largest area of relatively high summer SSTs.

Ice shelves large and small

The two largest ice shelves by area are located in West Antarctica: the Ross ice shelf in the Ross Sea and the Filchner-Ronne in the Weddell Sea. They have catchments in both West and East Antarctica. The third largest ice shelf is the Amery in East Antarctica (*see* Fig. 4).

The Ross and Filchner-Ronne ice shelves together cover 61% of the total Antarctic ice shelf area, yet contribute only 15% of the basal meltwater, while meltwater from considerably smaller ice shelves over only 8% of the area in the Amundsen–Bellingshausen seas account for *c.* 50% of the total meltwater (Fig. 5). This high melt/area ratio in West Antarctica is also found in some ice shelves in East Antarctica, such as the Totten ice shelf (Rignot *et al.* 2013) (Table 1).

Ross ice shelf

The Ross ice shelf, at 500,809km^2 (roughly the size of Spain) accounts for 32% of Antarctica's total ice shelf area (Stewart *et al.* 2019) (Fig. 6, *opposite*). DSW is formed in the Ross and Terra Nova Bay polynyas, limiting exposure to CDW and driving Mode 1 basal melting. The Ross Sea continental shelf is wide and therefore distant from the Antarctic Circumpolar Current, so warm Circumpolar Deep Water rarely reaches this region (Purkey *et al.* 2018). Ice Shelf Water reduces basal melting for most of the ice shelf and accretion reduces net mass loss. Typical of wide continental shelf regions, the Ross Sea has a residence time of six years, which allows Dense Shelf Water to collect at the seabed, salinify further and drive deep convection (Narayanan *et al.* 2019).

However, conditions are different in the north-western Ross ice shelf, where an area of 7,782km^2 has significantly higher seasonal basal melt rates than the shelf-wide average resulting from downwelling of solar-heated Antarctic Surface Water into the ice shelf cavity from the Ross polynya during the austral summer, driving Mode 3 basal melting. This area surrounds Ross Island, an important Ross ice shelf pinning point and

Table 1 Mean basal melt rates of six major ice shelves for the period 1992–2013 (in terms of area or basal melt rate; created from data in Rignot *et al.* 2013)

ice shelf	*area (km^2)*	*area melt rate (m/year)*
West Antarctica		
Ross	500,809	1.2 ± 0.2
Filchner-Ronne	338,887	0.7 ± 0.2
Thwaites	5,499	17.7 ± 1
Pine Island	6,249	16.2 ± 1
East Antarctica		
Amery	60,654	0.6 ± 0.4
Totten	6,032	10.5 ± 0.7

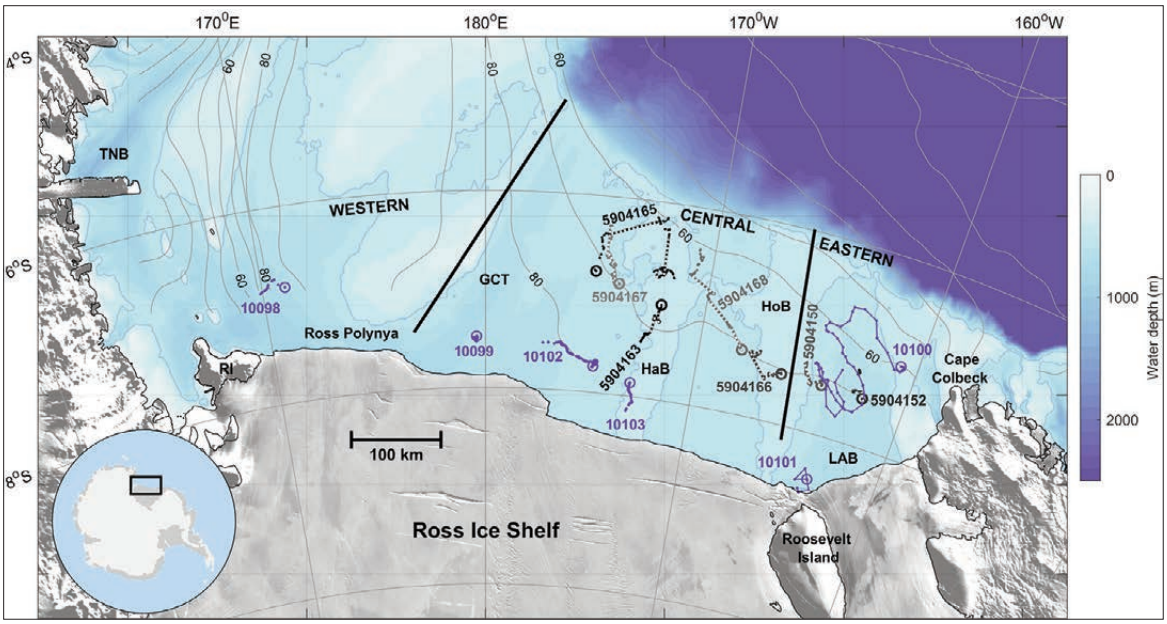


Figure 6 Map of the Ross Sea continental shelf, showing the western, central and eastern regions separated by bold black lines: TNB is Terra Nova Bay, GCT is Glomar Challenger Trough, LAB is Little America Basin, HaB is Hayes BankHoB is Houtz Bank; black and grey dots mark floats deployed in 2013 (image re-published with permission, AGU, from Porter et al. *2019).*

therefore structurally critical for the stability of the entire ice shelf. The mean basal melt rate in this area is 1.34m yr^{-1}, which indicates a basal mass loss of 9.5Gt yr^{-1}, and represents 20% of the entire Ross ice shelf net basal loss from only 1.6% of its area (Stewart *et al.* 2019).

Filchner-Ronne ice shelf

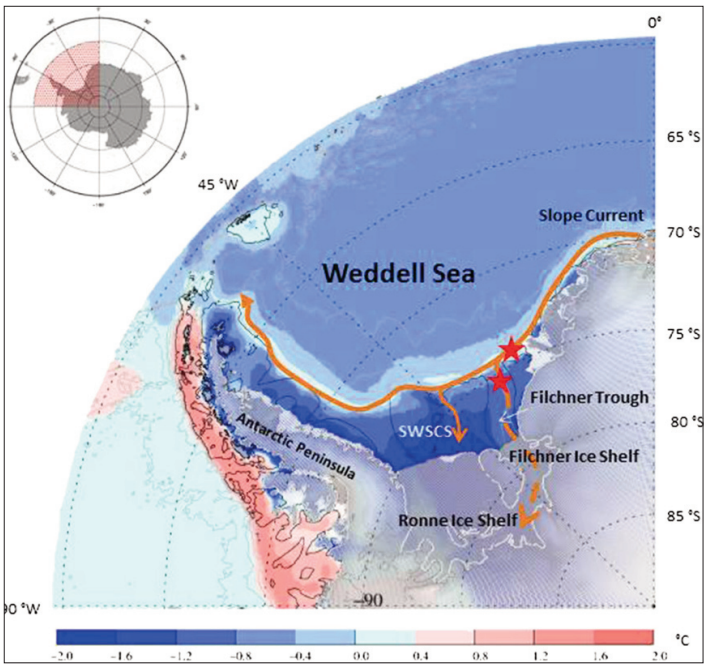
The Filchner-Ronne is the largest ice shelf in the Weddell Sea, and second only to the Ross ice shelf in size (Fig. 7). Fed by multiple ice streams, it drains a significant fraction of the Antarctic ice shelf. Like the Ross Sea continental shelf, the Weddell Sea continental shelf is also wide and CDW rarely reaches this region. However, since polar deep waters are warmer than surface water because their density is controlled by salinity rather than by temperature, a derivative of CDW called Warm Deep Water (*c.* 0.5˚C) upwells from the deep Weddell Sea and reaches the southern Weddell Sea continental shelf, where it is channelled through the Filchner Trough, to the Filchner-Ronne ice shelf. As it approaches the ice shelf front it is transformed to Dense Shelf Water (*c.* –1.9˚C) by strong sea ice formation, resulting in Mode 1 basal melting and consequent Ice Shelf Water production (Naughten *et al.* 2019).

However, Hellmer *et al.* (2017) warn that the Filchner-Ronne ice shelf could reach a tipping point this century owing to a change to Mode 2 basal melting, as the retreat of sea ice in a warming climate lets Warm Deep Water enter the Filchner-Ronne cavity (Timmermann *et al.* 2002). Modelling also shows increasing summer-intensified Mode 3 melting during the 21st and 22nd centuries owing to the reduced sea ice cover and increase in areas of open water (Timmermann and Goeller 2017).

Amery ice shelf

The Amery ice shelf, situated in Prydz Bay, East Antarctica drains the Lambert glacier system, which constitutes 16% of East Antarctica (Fig. 8, *overleaf*). Prydz Bay hosts three major polynyas, the Cape Darnley, the Mackenzie and the Barrier, of which the Cape Darnley produces the highest rates of sea ice in East Antarctica, while the MacKenzie is the primary source of the densest DSW. DSW is transported through a 500–600m deep trough centred in the Amery depression and into the ice shelf cavity, resulting in Mode 1 basal melting.

Figure 7 The southern Weddell Sea continental shelf, showing the Filchner and Ronne ice shelves and the Filchner Trough: bottom temperature based on NOAA's World Ocean Atlas 2001; slope current and flow of WDW onto the southern Weddell Sea continental shelf (SWSCS) marked in orange; flow into Filchner Trough and propagation toward the southern grounding line (light grey) marked by dashed orange arrow; red stars mark positions of profiles used for analysing the processes across the Filchner Trough; inset shows location in the Southern Ocean (image CC BY 4.0 © American Meteorological Society. Used with permission: from Hellmer et al. *2017, fig. 1 [see References for full citation].*



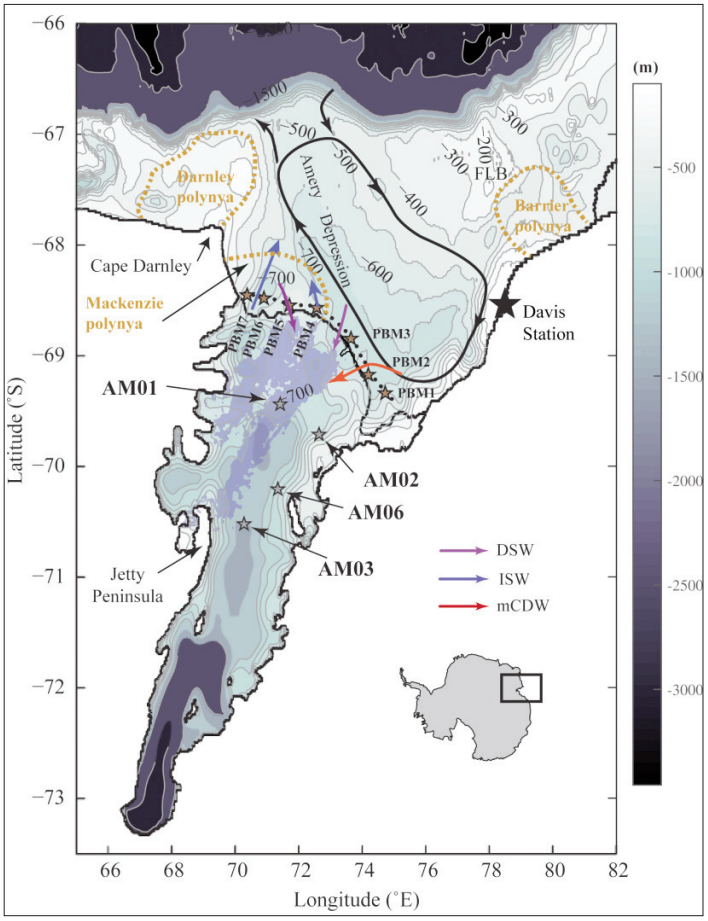


Figure 8 Map of the Amery ice shelf, showing polynyas, Amery depression and bathmetry mentioned in the text: brown stars are moorings and grey stars are boreholes; inset shows location of the Amery ice shelf in East Antarctica (image re-published with permission, AGU, from Herraiz-Borreguero et al. *2016).*

Amundsen Sea Embayment ice shelves

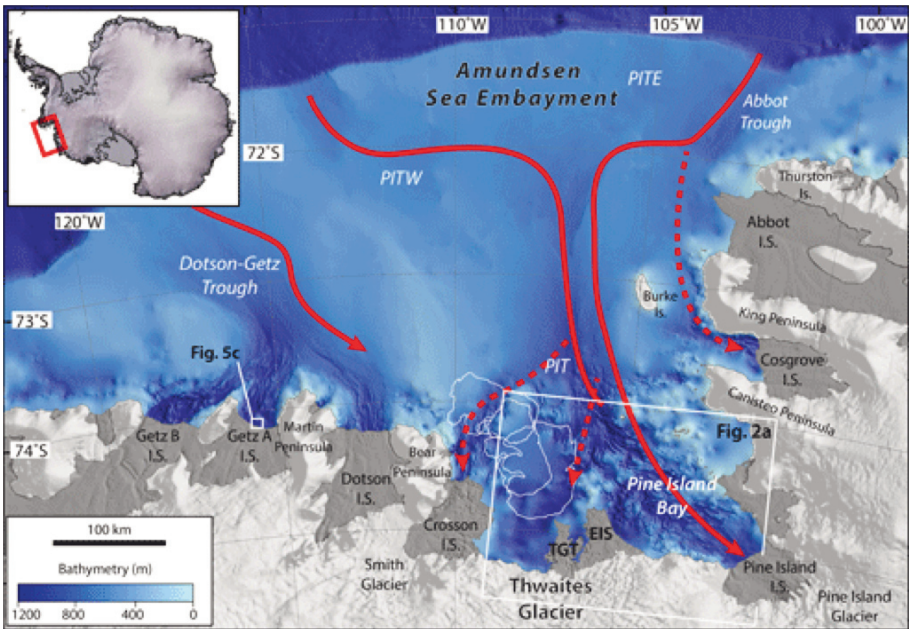
The Amundsen Sea Embayment (Fig. 9) hosts the most rapidly thinning ice shelves in Antarctica, notably the Thwaites and the Pine Island, which are the terminations of the Thwaites glacier and the Pine Island glacier. Together, these two glaciers accounted for more than 30% of the annual ice discharge from the West Antarctic Ice Sheet between 2009 and 2017 (Hogan *et al.* 2020). Thwaites ice shelf is made up of the Thwaites Glacier Tongue (TGT) and Eastern Ice Shelf (EIS). The Amundsen Sea Embayment is narrow and the proximity of the Antarctic Circumpolar Current enables CDW to be channelled onto the shelf and into ice shelf cavities through deep troughs, driving Mode 2 basal melting. The highest Pine Island ice shelf basal melt rates, *c*. 200–250m yr^{-1}, occur within these channels at *c*. 300–350m depth within *c*. 5km of the grounding line. Steep retrograde bedrock slopes (up to 2,500m below sea level) and deep basal keels (400–450m) enhance fast basal melting (Shean *et al*. 2019). Basal melt of these ice shelves supplies sufficient freshwater to the Amundsen Sea polynya to prevent convection to the sea floor, suppressing the formation of DSW (Silvano *et al*. 2018).

Satellite observations show the highest ice shelf melt rate on record, 20m yr^{-1} 2014–2017, on the Thwaites ice shelf (Milillo *et al.* 2019). Thwaites glacier was in the news in 2019 with the first cruise of the UK–US International Thwaites Glacier Collaboration (ITGC) project, which mapped the seabed in detail for the first time. The troughs shown in Figure 9 were found to be connected and significantly deeper (up to 600m deep) and wider than previously thought, forming pathways for CDW to the ice shelf base. A retrograde bed slope directly connected to the WAIS interior and small rapidly thinning ice shelf, part of which (TGT) has no pinning and therefore no buttressing effect, implies that Thwaites glacier is particularly susceptible to retreat due to marine ice sheet instability (Hogan *et al.* 2020). High rates of glacier flow acceleration are observed, with an estimated increase in net mass loss from 4.6Gt yr^{-1} from 1979 to 1989, to 34.9Gt yr^{-1} from 2009 to 2017 (Rignot *et al.* 2019). With implications for wider WAIS retreat, Thwaites glacier has been called the 'Doomsday Glacier'.

Totten ice shelf

The Totten ice shelf on the Sabrina coast buttresses a marine-based ice volume equivalent of more than 4m of global sea level rise and has the highest basal melt rate in East Antarctica (Fig. 10, *opposite*). Ship-based oceanographic observations in January 2015 showed deep (maximum depth 1,097m) troughs at 600m in front of the Totten ice shelf cavity containing a thick layer of CDW (–0.4˚C to –0.6˚C) (Rintoul *et al.* 2016). At the

Figure 9 The Amundsen Sea Embayment, showing the ice shelves and bathymetric troughs: arrows show observed (solid) and inferred (dashed) CDW pathways towards grounding zones of Pine Island and Thwaites ice shelves; PIT is Pine Island Trough; PITE is Pine Island Trough East; PITW is Pine Island Trough West; TGT is Thwaites Glacier Tongue; EIS is Eastern Ice Shelf (image CC BY 4.0: Hogan, K. A., Larter, R. D., Graham, A. G. C., Arthern, R., Kirkham, J. D., Minzono, R. T., Jordan, T. A., Clark, R., Fitzgerald, V., Wåhlin, A. K., Anderson, J. B., Hillenbrand, C-D., Nitsche, F. O., Simkin, L., Smith, J. A., Gohl, K., Arndt, J. E., Hong, J., and Wellner, J. 2020 'Revealing the former bed of Thwaites Glacier using sea-floor bathymetry: implications for warm-water routing and bed controls on ice flow and buttressing'. The Cryosphere ***14****, 2883–2908; doi.org/10.5194/tc-14-2883-2020 (accessed 1/11/2020).*



2,300m deep grounding line (one of the deepest in the world) this water mass would be 3.2˚C above the local freezing point. A *c.* 1,000m deep trough containing CDW (–1.3˚C) was also found in front of the neighbouring Moscow University ice shelf. An ocean modelling simulation shows year-round stratification and freshening in the Dalton polynya from glacial meltwater released by the Moscow University ice shelf. DSW is not formed, thereby enabling CDW to reach the base of the Totten ice shelf where it drives Mode 2 basal melt (Silvano *et al.* 2017).

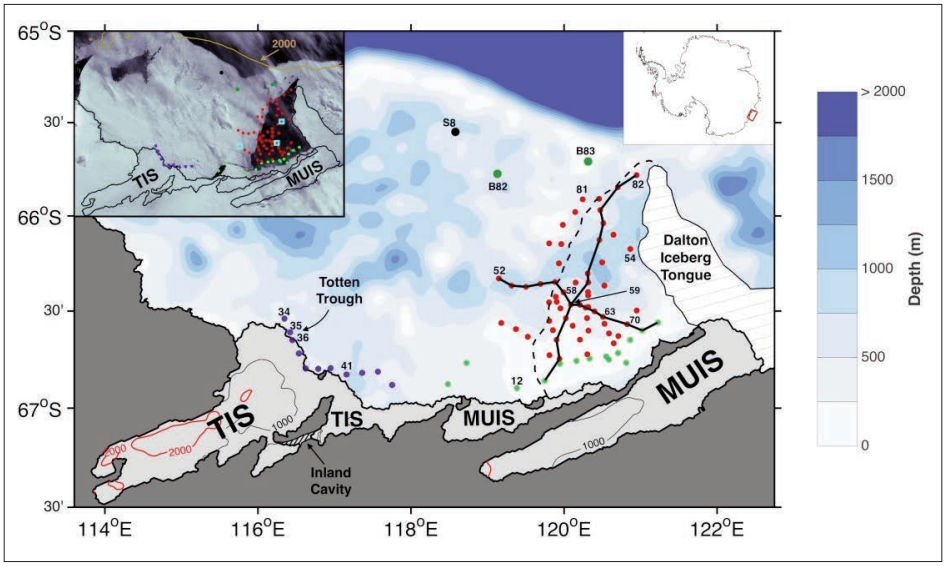
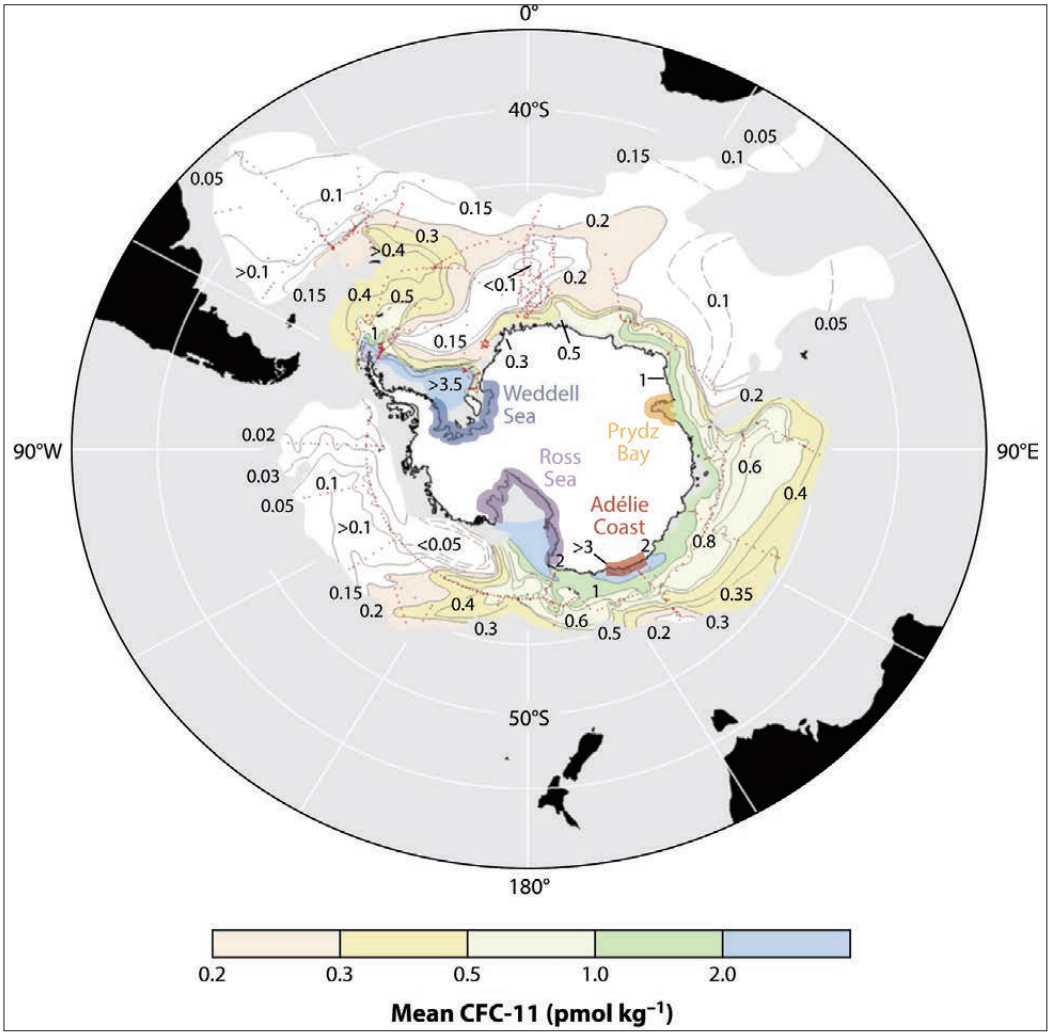


Figure 10 Totten Ice Shelf and neighbouring Moscow University Ice Shelf (MUIS) on the Sabrina Coast, East Antarctica: red, green, and blue dots indicate the location of stations in the Dalton Polynya, in proximity to the MUIS, and the Totten Ice Shelf (TIS) calving fronts, respectively (published with permission from AGU Advances*).*

Ocean freshening and the slow-down of Antarctic Bottom Water formation

Ocean freshening stems from meteoric sources (ice shelf basal melt, iceberg melt and direct precipitation), and sea ice melt, of which ice shelf basal melt is likely to be the most significant contributor. The World Oceanographic Circulation Experiment (WOCE) Hydrographic Programme 1990–1996, and more recently Climate and Ocean Variability, Predictability and Change (CLIVAR)/CO_2, and Global Ocean Ship-based Hydrographic Investigation Programme (GO-SHIP) 2001–2017 have monitored water mass properties in the Southern Ocean and the transport of Antarctic Bottom Water to the Equator using chlorofluorocarbons (CFCs) and natural tracers over the past 35 years (Purkey *et al.* 2018) (Fig. 11). The data collected by these projects show freshening of all four varieties of AABW, which, together with observed warming, indicates a decline in AABW volume around Antarctica in the last three decades, reaching the Pacific, Indian and Atlantic oceans. The four varieties of AABW — formed from Dense Shelf Water — are Weddell Sea Bottom Water, Ross Sea Bottom Water, Adélie Land Bottom Water and Cape Darnley Bottom Water, formed in the Weddell Sea, Ross Sea, Adélie Coast and Prydz Bay, respectively (Purkey *et al.* 2019). Of these, Ross Sea Bottom Water and Weddell Sea Bottom Water are the most significant components of AABW.

Figure 11 Map showing the four regions of AABW formation (Ross Sea, Weddell Sea, Adélie Coast and Prydz Bay) from mean concentrations of the chlorofluorocarbon CFC-11 (red dots indicate WOCE data collection; after Purkey et al. *2018; reproduced with permission from Springer Nature [fee waived] under Creative Commons Attribution 4.0 International License).*



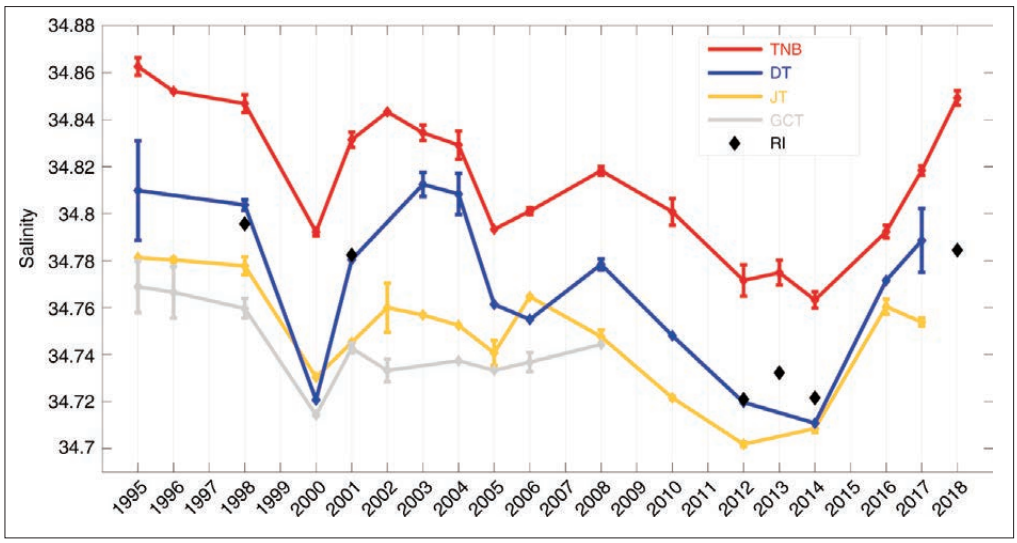


Figure 12 Time series of DSW salinity in the Ross Sea for each austral summer 1995–2018 (after Castagno et al. *2019; reproduced with permission from Springer Nature [fee waived] under Creative Commons Attribution 4.0 International License).*

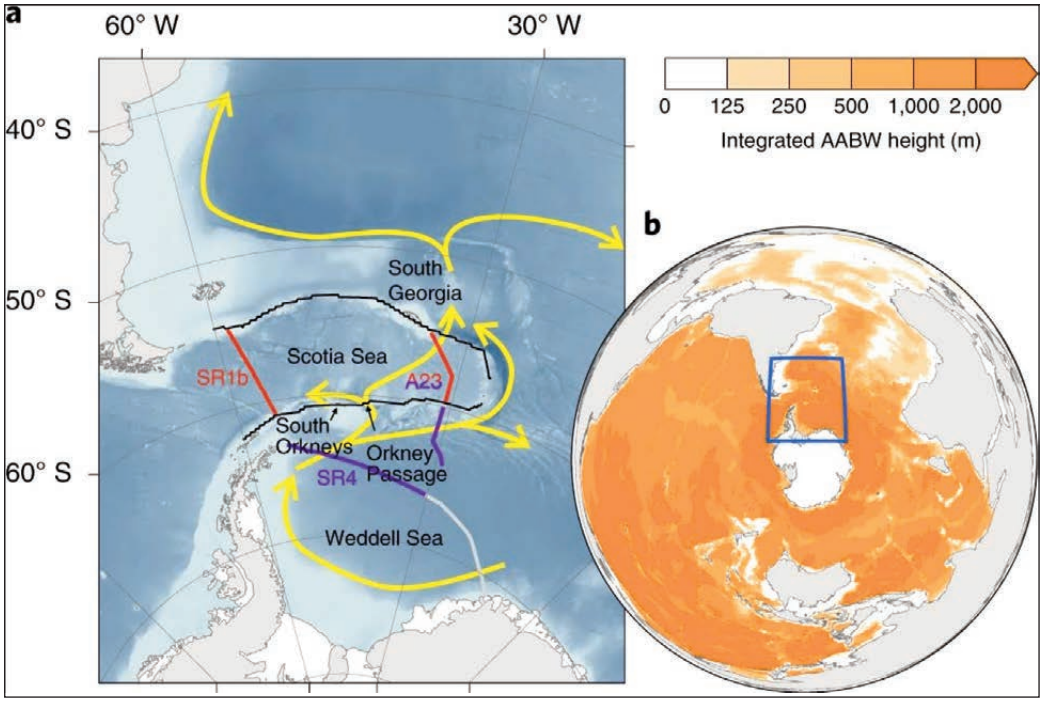
Will sea ice increase?

Castagno *et al.* (2019) show a sharp salinity rebound from 2014 to near 1995 values in the Ross Sea. Figure 12 shows data from Terra Nova Bay and Ross Island, which are persistent polynyas where DSW is formed, and the three troughs through which it is transported. A sharp increase in salinity is observed after 2014 at each location (with the exception of GCT, which was not observed after 2008). This salinity rebound could be because of a sustained increase in annual sea ice production in the Ross and Terra Nova Bay polynyas or from a reduction in freshwater input. The increase in the West Antarctic Ice Sheet mass loss in the past two decades (largely because of basal melting), would decrease rather than increase salinity. An additional annual average anomaly of 64km^3 yr^{-1} of sea ice would, however, account for the salinity anomaly (Castagno *et al.* 2019). The Ross and Terra Nova Bay polynyas combined produced 438 ± 72km^3 yr^{-1} of sea ice from 1992 to 2013 (Tamura *et al.* 2016). Therefore an increase in sea ice formation is the likely cause of the salinity anomaly after 2014.

This anomaly coincides with an observed increase in AABW exported from the Weddell Sea to the Atlantic Ocean. Pathways of AABW from the Weddell Sea into the Atlantic have been inferred from ship-based data collected by the National Oceanographic Centre (Southampton) and the British Antarctic Survey along sections in the Weddell and Scotia seas since 1989 (Fig. 13). Figure 14 *(opposite)* shows a recovery of Lower Weddell Sea Deep Water (LWSDW), the densest class of AABW that is exported from the Weddell Sea, from 2014 to 2018. This could be accounted for by the upward trend of sea ice production in the Weddell polynya, the second most productive in Antarctica.

The overall trend of sea ice production in Antarctica has been upward since the 1990s, the likely cause being that meltwater results in stratification of the water column, which in turn impedes Circumpolar Deep Water from reaching surface waters, and leads to a reduction in SST. Simulations show that sea ice decreases after 2060 when ocean warming overrides the cooling effect of stratification (Fig. 15, *opposite*). However, increased glacial melt in a warming ocean would cause negative feedback by increasing stratification, potentially causing a return to increased sea ice and Dense Shelf Water formation, thus reducing basal melting and reversing the apparent switch to Modes 2 and 3 basal melting of the Filchner-Ronne and Ross ice shelves. AABW formation would increase, strengthening MOC. Simulations accounting for Antarctic meltwater show that reduced SST and surface air temperature would delay the exceedance of the IPCC warming targets of 1.5˚C and 2˚C by more than a decade, as 0.5˚C–3.5˚C of atmospheric warming is offset (Golledge *et al.* 2019).

Figure 13 AABW pathways from the Weddell Sea: (a) Map of the Scotia Sea: black lines mark south and north Scotia ridges — these sections have been partially or fully occupied since 1989; data is currently (February 2021) being collected on the A23 and SR1b repeat hydrographic sections from onboard the RRS James Cook*, in order to extend these time series. Red lines mark Scotia Sea sections; purple lines mark Weddell Sea sections; yellow arrows mark schematic pathways of AABW. (b) Map showing global extent of AABW, based on World Ocean Atlas data, 2013 — study area outlined in blue (after Abrahamsen* et al. *2019; reproduced with permission from Springer Nature [fee waived] under Creative Commons Attribution 4.0 International License).*



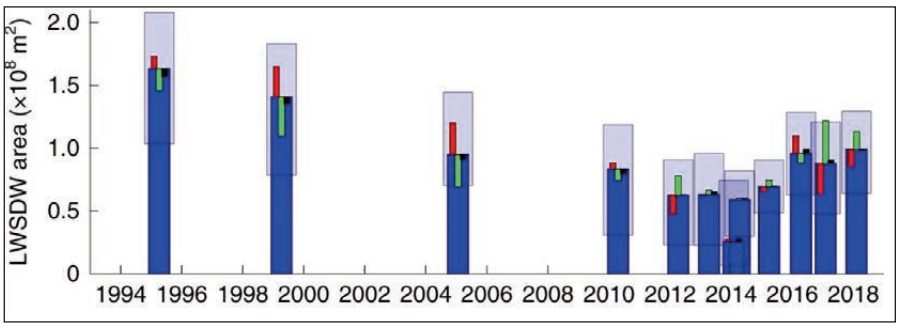
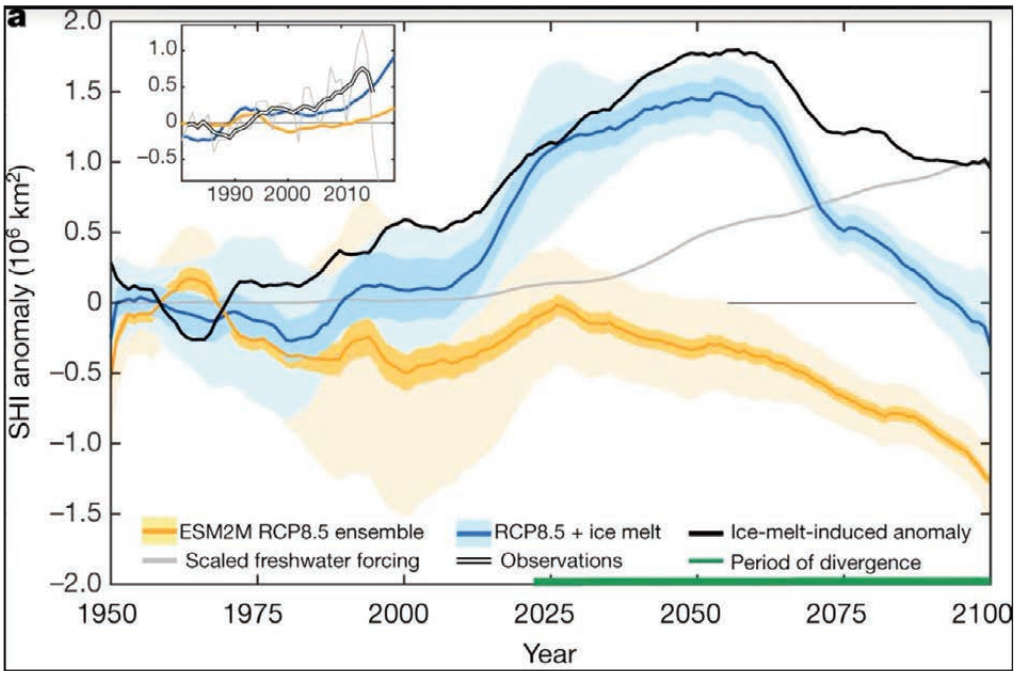


Figure 14 Area of LWSD from the A23 section in the Scotia Sea (after Abrahamsen et al. *2019; reproduced with permission from Springer Nature [fee waived] under Creative Commons Attribution 4.0 International License).*

That said, projections for RCP4.5 and RCP8.5 show a near collapse of AABW by 2200 owing to meltwater-induced freshening. Projections to 2100 show a weakening of Antarctic Circumpolar Current transport through Drake Passage (Naughten *et al.* 2018), which implies reduced AABW transport to the ocean basins, resulting in weakened global ocean circulation. This is clearly at odds with the upward trend in sea ice, salinity rebound in the Ross Sea and recovery of Weddell Sea AABW. MOC is driven on a timescale of 1,000 to 2,000 years (Oshima *et al.* 2016); therefore a change in global ocean circulation would have global consequences during at least the next millennia.

Whether Southern Ocean sea ice extent will decrease or increase through this century and beyond is uncertain, and will be linked to the magnitude of climate warming. What is clear is that continuous monitoring of Southern Ocean sea ice, ice shelf basal melting and changes in AABW is essential if we are to understand this highly dynamic, fast-changing environment and its impact on the Earth system.

Figure 15 Annual mean sea ice anomalies in the Southern Hemisphere relative to the 1950–1970 mean, from a large ensemble simulation of a CMIP5 climate model: inset shows 1980–2020, with the black line indicating observed anomaly from the National Snow and Ice Data Center (NSIDC) relative to the 1880–2000 mean; period of divergence between standard and meltwater ensembles shown by green bar (after Bronselaer et al. *2018; reproduced with permission from Springer Nature [fee waived] under Creative Commons Attribution 4.0 International License).*



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Rocky foreign visitors: the erratic population of Yealand Conyers, Carnforth, Lancashire

Duncan Woodcock

The parish of Yealand Conyers lies about three miles north of Carnforth, where it occupies an area of *c.* 6 km^2. A wooded limestone ridge runs north–south down the centre of the parish. To the west, the land drops away steeply to the swampy, reed-covered area of Leighton Moss. Eastwards from the ridge, the land slopes down more gradually over farmland towards a broad 'corridor' that contains a series of drumlinoid ridges that also trend roughly north–south. Within this corridor run two main roads, the West Coast mainline railway and the Lancaster Canal. About 20ka ago, during the Last Glacial Maximum, the corridor was a major route for ice flowing southwards from the higher ground of the Lake District to the north.

The bedrock of Yealand Conyers comprises Lower Carboniferous (Arundian to Asbian) limestones of the Great Scar Limestone Group. Although these limestones are intermittently exposed on small scars along the central ridge, most of the bedrock lies beneath a blanket of glacially derived sediments, including tills and fluvioglacial sands and gravels.

Although 'till' is the modern term to describe the unsorted sediments deposited beneath and at the margins of glaciers, the older term 'boulder clay' is an excellent descriptor of the type of till deposited locally. While the finer-grade material provides for the development of good farmland, the larger material has been a source of some difficulty to farmers in the past. John Lucas, in his history of Warton parish (which then included Yealand Conyers), describes the soil as "… a Mixture of Earth and Gravel" and comments at length on "… the great Quantity of Stones that are found therein … the most mischievous are those that are covered with Soil but are not out of the Way of the Plow". Such 'stones' required removal, either by the digging of pits to bury adjacent stones below plough depth or by blowing them up with gunpowder (Lucas *c*. 1740). Smaller boulders at or near the surface were collected and removed to field boundaries, where they were used to construct drystone walls (Fig. 1). Local agricultural contractors still advertise 'stone removal' as one of their offerings.

Figure 1 This section of drystone wall at SD 5148 7468 is c. *1.5m high and is constructed almost entirely from greywacke erratics that were probably cleared from the adjacent field.*

Figure 2 This large (c. 2m wide) boulder is the largest of four Shap granite erratics at SD 5017 7439, where they were placed along a field boundary adjacent to a gate and squeeze stile.

In Lucas's time, the local farmers regarded the 'stones' as a nuisance and cared little about their origins. In Beetham parish, some three miles north of Yealand Conyers, the Reverend William Hutton had sufficient leisure time to record his observations of local folklore and natural history while he was vicar from 1762 to 1811. Hutton was a keen observer, who noticed that some of the rocks in the area were "foreign visitors". Of such rocks he wrote that "…the Country People have given them nicknames innumerable … The Granite, the Callierd and the Blew ragg were found formerly on our Field Land. Agriculture had driven them into the bottom of Fences and into the foundations of old Houses" (Hutton 1770). Hutton believed that these erratics had been transported to Beetham during the Deluge. It was not until the 1830s that Swiss-American natural historian Louis Agassiz proposed that they had been transported by ice.

Most of the local erratics were sourced from the Lake District. Of these, the most distinctive group is those derived from the granite outcrop at Shap (Fig. 2), a granitoid rock characterised by conspicuous large, pink alkali feldspar megacrysts (Fig. 3).

Figure 3 A close-up view of the surface of the erratic in Figure 2. The pink alkali feldspar megacryst is c. *40mm long.*

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Figure 4 This prominent Shap granite erratic at Beetham is known locally as the Rent Stone (photograph by Peter Standing — published with permission).

Although these erratics are not common in the local area, they were clearly recognised as something special and often preserved in prominent locations. Within Yealand Conyers there are two large boulders of Shap granite around an old water pump, with another group of four adjacent to a gate no more than 100m uphill from the pump. In Beetham parish, a large Shap granite erratic is known locally as the 'Rent Stone' (Fig. 4), so called because it is said to be where tenants paid their rent.

The most common type of glacial erratic in the parish is, without doubt, Hutton's 'Blew ragg'. These are greywackes from the Windermere Supergroup, a lithology that has its nearest outcrops no more than 10km north-east on the other side of the River Kent estuary. The greywackes tend to weather to a slightly brownish colour; they can be spotted easily in a wall that comprises a mix of erratics and limestone blocks (Fig. 5). A freshly broken surface is medium grey in colour (Fig. 6), often with a slight bluish tinge in bright sunlight (perhaps explaining the 'Blew ragg' name). The fragmental texture of these fine- to medium-grained sandstones is not always obvious in hand specimen; Tucker (2001) describes these rocks as being well indurated and superficially looking like dolerite.

Figure 5 A drystone wall constructed from a mix of greywacke erratics (brown weathered surfaces with pale greenish grey lichen) and limestone blocks (grey weathered with white and orange lichen).

The third type of erratic — Hutton's 'Callierds' — comprises a variety of rock types sourced from the Borrowdale Volcanic Group (BVG). These erratics often weather to a light grey surface. They range in composition from aphyric dacites that need a thin section to display their original ignimbrite texture, to volcanic breccias in which angular clasts are conspicuous on a weathered surface (Fig. 7). These BVG erratics can show a wealth of detail in hand specimen on a fresh surface (Fig. 8, *opposite*). An additional sample from the erratic shown in Figure 7 contains a small red garnet; such garnets are unusual but not unknown in BVG rocks (Fitton 1972).

In qualitative terms, one gains an impression that the greywacke erratic is by far the most common type, with far fewer BVG or Shap granite erratics. A more quantitative view can be obtained from Peter Standing's study of erratics trapped within grykes on limestone pavements. Out of the 200 or so gryke erratics found within the Arnside and Silverdale AONB, some 95% are greywackes, with the remaining 5% comprising various BVG rocks, with not a single Shap granite gryke erratic recorded (Standing 2010). If the chance of a given erratic becoming trapped in a gryke is independent of type, such a distribution is probably what one might expect from the proximity and size of the source areas for the different types of erratic. That there are, comparatively, so many Shap erratics on display emphasises the fact that they were seen as distinctive and 'special'.

Figure 6 A freshly broken surface of a greywacke erratic. The slightly bluish tinge to this medium grey rock may account for its local name 'blew ragg'. The end of the hiking pole is 20mm thick.

*Figure 7 This large (*c. *1m wide) boulder is the largest of several BVG erratics around SD 5097 7408.*

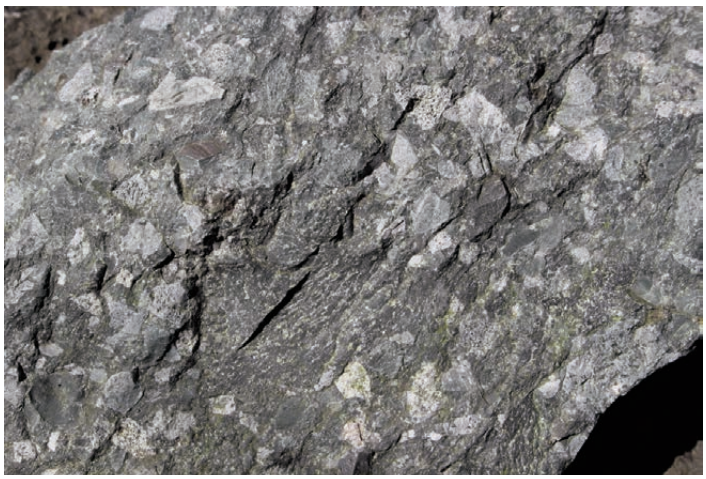

Figure 8.Close-up view of the fresh surface of a hand specimen collected from the BVG erratic shown in Figures 7 and 8 (field of view 100mm ¥ 70mm).

Figure 9 shows the 'erratic population' within the parish of Yealand Conyers. Greywacke erratics are far too numerous to record individually. I am aware of a total of eight Shap granite erratics: six in the area of the old water pump, one recently dug up by the side of Peter Lane at SD 4966 7379 and one small one that we dug up while trenching on our land to install fibre optic broadband cabling with B4RN in 2015. As far as I am aware, there are a total of ten BVG erratics: two of these are within walls (one is shown in Fig. 10, *overleaf*), a further seven are free-standing boulders of various sizes adjacent to public footpaths, and one is on private land. There must be many more erratics within the parish: on private land, within areas of thick woodland or still buried beneath the surface.

Figure 9 Map of the central portion of Yealand Conyers parish, showing the location of known Shap granite (orange stars; figure indicates number at locality) and BVG (blue circles) erratics.

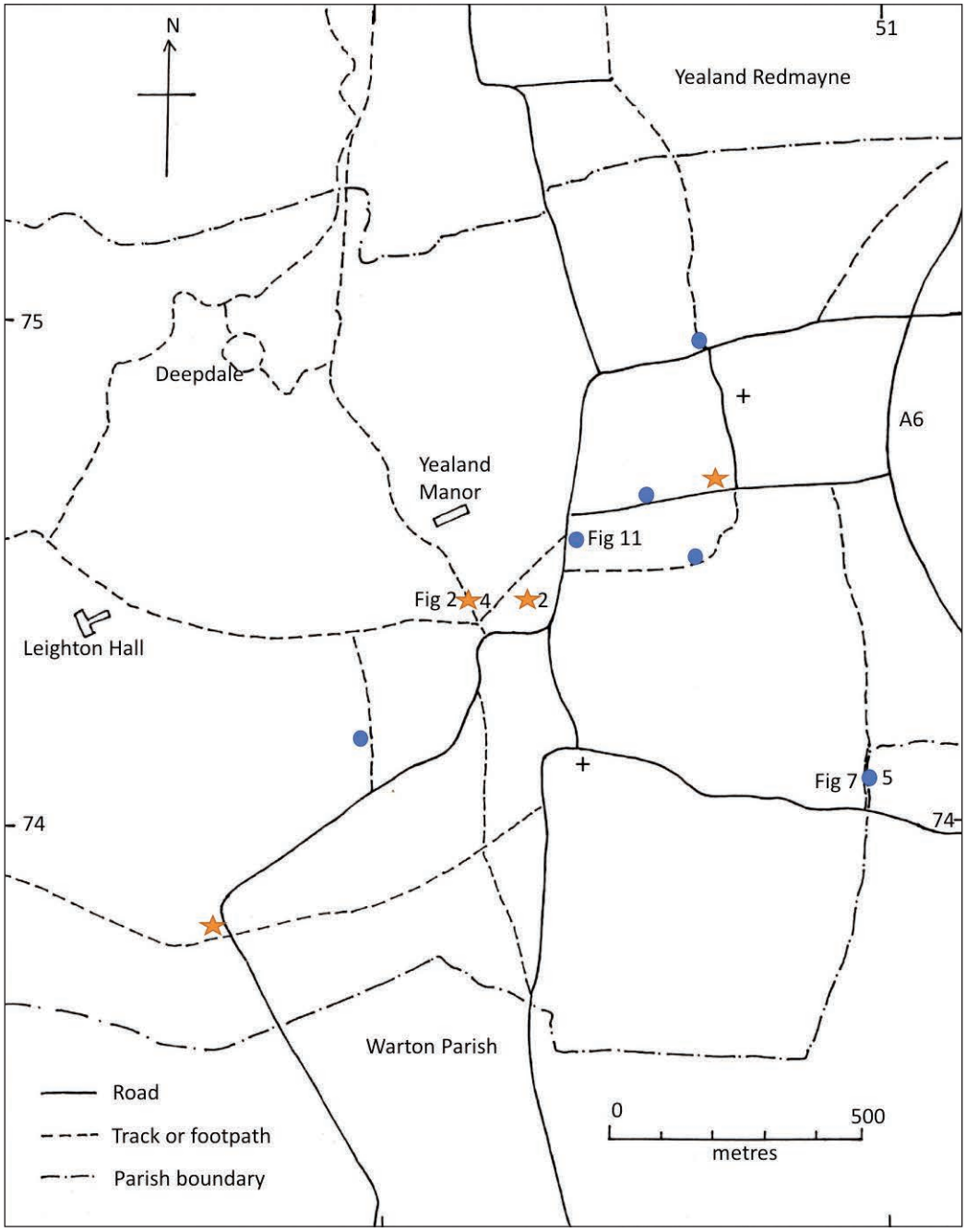

Figure 10 This BVG erratic, c. *0.3m long, is conspicuous within a wall of limestone blocks at SD 5036 7457.*

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Fulgurites!

Colin Morley

As a part of my collection of rocks, fossils and minerals, I have some items that do not fit into any of those three categories. I thought that I would share one of these specimens with you. While I am sure that many of you will know exactly what a fulgurite is, I am equally sure that many others will not. But even if you do know, please read on; there may be things that you did not know. My fulgurite came from the Sonoran Desert in Arizona (Figs 1 and 2).

Figure 1 Characteristic Sonoran Desert (Colin Morley).

Figure 2 Fulgurite found by the author (Colin Morley).

In simplistic terms a fulgurite is a 'petrified lightning strike' or a 'trace fossil' from lightning (Fig. 3, *overleaf*). Fulgurites are formed when lightning strikes the ground, or, to be a little more precise, fulgurites are formed by the rapid heating of rock or soil by a cloud-to-ground lightning strike. They get their name, very appropriately, from the Latin term for lightning: *fulgur*.

Fulgurites are the most widespread variety of natural glass, and they are capable of forming wherever lightning strikes. However, that does not mean they are the most common variety or source of natural glass. It just means that lightning is a ubiquitous phenomenon on Earth, striking the surface *c*. 65 times each second (Borucki and Chameides 1984). You may never have thought about it much, but a lightning discharge occurs when a portion of the atmosphere attains an electrical charge sufficient to cause breakdown of the air within the electric field. This field is thought to be produced by the charging of ice particles or water droplets as they collide and are separated by internal circulatory patterns within clouds. Stray electrons further ionise the air along a conductive channel, which can reach from cloud-to-cloud, cloud-to-air, or cloud-to-ground. Lightning may dissipate up to

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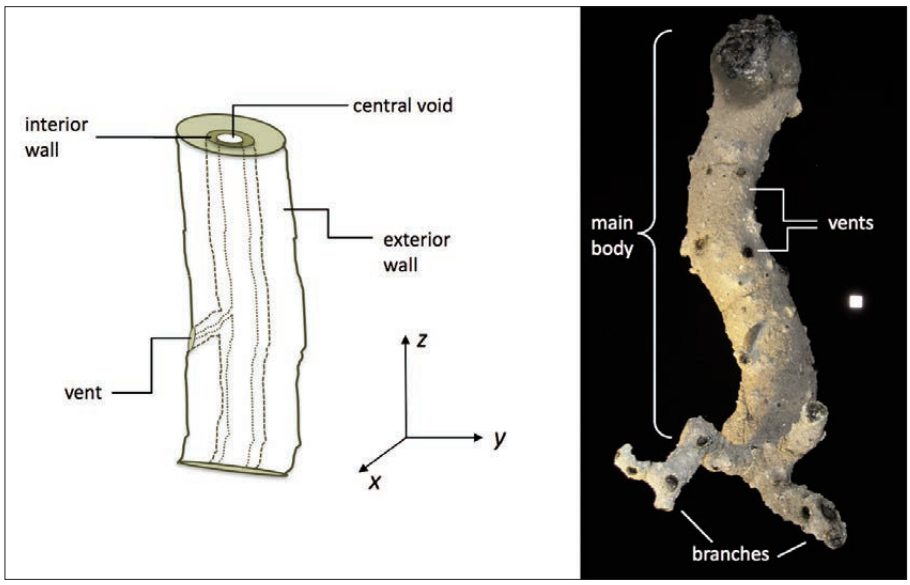


Figure 3 Fulgurite anatomy (Colin Morley)

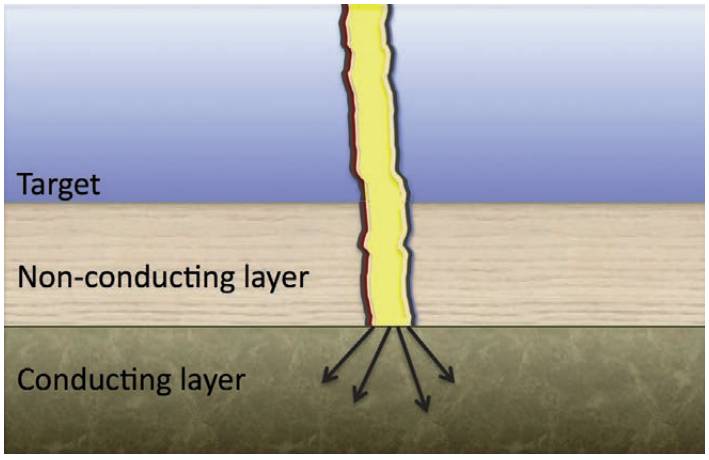
109J per flash (Borucki and Chameides 1984), heating the surrounding air to instantaneous temperatures in the range of 105K (Borucki and Chameides 1984). Some of the gases formed force their way out and create tiny vents on the fulgurite main body.

When the discharge strikes the ground it is probably more than 100 million volts. This voltage rapidly melts and vaporises silica-rich sand and soil vitrifying mineral grains. On striking the ground the electricity takes the path of least resistance through the soil, giving us the familiar dendritic branching pattern that we associate with lightning. The proper name for the pattern is 'LichtenbergFigures' (*see* Box 1).

A lightning strike creates a fulgurite when it is powerful enough to pass through a relatively non-conductive area to dissipate in the more conductive layers of the subsurface. Once the strike has breached the non-conductive zone it produces those wonderful Lichtenberg Figures that we associate with the flash of lightning in the sky (Fig. 4).

There is a large variation in the composition of fulgurites; and this variety appears to reflect the diverse target materials present on the Earth's surface (*see* Box 2). This variety leads to different classifications of fulgurite types. In spite of having a name end-ing in '–ite', fulgurites are not a mineral. They are usually classi-fied as a variety of a mineraloid called 'lechatelierite' (*see* Box 3)

Figure 4 Formation of fulgurite (Colin Morley).



and are listed in the quartz group. Nevertheless, not all fulgurites are lechatelierites. In order to be a true lechatelierite the original sand must be nearly pure silica.

Desert areas, such as the Sonoran Desert, provide ideal areas for producing good fulgurites. Fulgurites can also be caused by downed high voltage power lines, and such occurrences have produced brightly coloured lechatelierites, due to copper or other materials from the power lines themselves.

Brightly-coloured lechatelierites resembling fulgurites are usually synthetic and reflect the incorporation of synthetic materials. However, lightning can also strike man-made objects, even resulting in coloured fulgurites.

Let me tell you how and where I found my couple of pieces of fulgurite.

To misquote Douglas Adams ,"There's this guy y'know". He lives in Arizona and he has a hobby. It is not a common hobby. In fact, I am not sure that the hobby has a name. He goes out into the desert and hunts for the small circular marks that indicate lightning strikes. When he finds one, he excavates and uncovers the now fused silicon-rich inverted dendritic shape (the Lichtenberg figure) created by the lightning strike. It is quite tricky to excavate because it is now made of fused silica — a natural glass.

He clears out the hole as carefully as an archaeologist exposing fragile bones. As he proceeds, the 'branches' of the Lichtenberg figure need support. He uses wooden battens and poles to stop the whole structure from collapsing. When the shape is cleared he sets up his camera for a photograph (Fig. 5, *opposite*).

The last stage is to get as much of it out in one piece as possible. The hole can be about six or even eight feet deep and the branching shapes he has exposed are amazing. He also has buckets full of much smaller pieces. Well, it is glass!

I am fortunate that my own piece of fulgurite is larger than average (*see* Fig. 1).

Even small museum collections are frequently maintained more for their appearances rather than for the purposes of scientific study. However, the petrology of fulgurites is fascinating, for instance in Type 1 fulgurites the groundmass often largely consists of nearly pure SiO_2 glass, with infrequent, small areas of increased Al_2O_3 or TiO_2 abundance. This is probably due to

Box 1 Lichtenberg figures

Named after the German physicist Georg Christoph Lichtenberg, who originally discovered and studied them, they were first discovered in 1777. It was thought that their characteristic shapes might help to reveal the nature of positive and negative electric 'fluids'. Lichtenberg built a large electrophorus to generate high voltage static electricity. After discharging a high voltage point to the surface of an insulator, he recorded the resulting radial patterns by sprinkling various powdered materials onto the surface. By pressing blank sheets of paper onto the patterns, Lichtenberg was able to transfer and record these images, thereby discovering the basic principle of modern xerography.

Box 2 Classification of Fulgurites

Fulgurites are classified by Pasek et al. (2012) as five types, related to the type of sediment in which the fulgurite formed, as follows:

• Type I: Sand fulgurites with tubaceous structure; their central axial void may be collapsed.

• Type II: Soil fulgurites; these are glass-rich, and form in a wide range of sediment compositions, including clay-rich soils, silt-rich soils, gravel-rich soils, and loessoid; these may be tubaceous, branching, vesicular, irregular/slaggy, or may display a combination of these structures, and can produce exogenic fulgurites (droplet fulgurites).

• Type III: Caliche or calcic sediment fulgurites, having thick, often surficially glazed granular walls with calcium-rich vitreous groundmass with little or no lechatelierite glass; their shapes are variable, with multiple narrow central channels common, and can span the entire range of morphological and structural variation for fulguritic objects.

• Type IV: Rock fulgurites, which are either crusts on minimally altered rocks, networks of tunnelling within rocks, vesicular outgassed rocks (often glazed by a silicide-rich and/or metal oxide crust), or completely vitrified and dense rock material, and masses of these forms with little sedimentary groundmass.

• Type V: 'Droplet' or 'exogenic' fulgurites that show evidence of ejection (e.g. spheroidal, filamentous or aerodynamic), related by composition to Type II and Type IV fulgurites.

Box 3 Lechatelierite

Lechatelierite also forms as the result of high-pressure meteorite impact cratering and is a common component of a type of glassy ejecta called tektites (Fig. 6). Most tektites are blobs of impure glassy material, but tektites from the Sahara Desert are known as 'Libyan desert glass' and are composed of almost pure silica, making it almost pure lechatelierite.

Shock pressures of about 85GPa are needed to produce lechatelierite in quartz grains. For example, lechatelierite was formed during the impact of a meteorite into a layer of Coconino Sandstone at Meteor Crater in Arizona. During the rapid pressure reduction following the impact, steam expanded the newly formed lechatelierite. The shattered and expanded glass has a density less than that of water.

Lechatelierite was also formed artificially, as in trinitite produced by melting of quartz sand at the first nuclear bomb explosion at Trinity Flats, White Sands, New Mexico.

Figure 5 Tektite (photograph © Hilary Barton).

Figure 6 Example of exposed Fulgurite in California (US National Parks Service: Public Domain).

isolated ilmenite or other melted grains. No significant visual or compositional difference is seen across their thin walls, and the elemental quantities are nearly uniform, regardless of distance from the central hole.

Many high-pressure, and high-pressure plus high-temperature materials have been observed in fulgurites. And many of these minerals and compounds, including reduced phosphides (in the form of schreibersite), are quite rare on earth because of our oxygen rich atmosphere.

It is possible that studies into fulgurites could be important for discoveries on other planets. Non-terrestrial lightning has been most notably observed by the Voyager spacecraft within the atmospheres of Jupiter (Daly *et al*. 1993). The subject of lightning strikes on Venus is quite controversial at the moment, but lightning has been theorized to exist in the martian atmosphere.

Due to its thick atmosphere and rich hydrocarbon composition, Titan has been a popular subject for the possibility of lightning, but unfortunately the atmosphere prevents detection at optical wavelengths.

The research on earthly fulgurites will help to design instruments for future atmospheric research on other planets.

(A version of this article was originally published in Footnotes, *OUGS Wessex Branch, June 2020, 3–5 — Ed.)*

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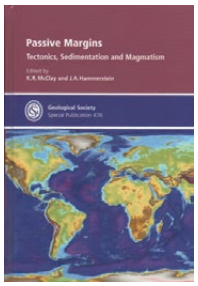
Book review



McClay, K. R., and Hammerstein, J. A. (eds) 2020 *Passive Margins: Tectonics, Sedimentation and Magmatism*. London: Geological Society Special Publication 476 (978-1-78620-385-4; 447pp; hardback £160)

Geological Society Special Publications are not intended to be textbooks on their subject matter. However, they are intended to provide balanced coverage of the subject and full peer review is performed on all the papers included.

This particular volume comprises papers written in memory of Professor David Roberts and covers the key findings from recent research on passive margins. Subjects covered are tectonics, bathymetry, stratigraphy and sedimentation, structural evolution and magmatism. There is also a paper covering the wide-ranging professional life of Professor Roberts himself and the huge contribution he made to the field of geoscience.

All the papers are available online from the Geological Society's Lyell Collection, which can be accessed free of charge from the OU Library for those who are still students or staff at the OU.

A number of the papers included focus on the development of the Atlantic Ocean, using a range of techniques including seismic analysis, gravity anomaly inversion and plate-cooling theory to investigate the Atlantic basin and its margins. The resulting images are of very high quality, but it can be difficult to fully interpret them from the book. Online access and the facility to expand them would prove beneficial.

A further group of papers looks at the North West Shelf of Australia, which underwent rifting in the Late Paleozoic and Mesozoic eras. Seismic surveys are used to analyse the complex extensional fault structures in this region.

Further analysis of rift faulting is covered in a paper on the south-east Mediterranean passive margin. This region underwent rift and transform faulting during the break up of Gondwana and the subsequent evolution of the Neotethys Ocean. Many of these faults were later reactivated when the Neotethys Ocean closed due to the convergence of the African-Arabian and Eurasian plates.

Further focus on the Mediterranean is provided by a paper on the depositional and erosional features of the contourites of the Iberian continental margin. These are thought to record Mediterranean Outflow Water, following its exit through the Strait of Gibraltar. In addition to their possible use as hydrocarbon reservoirs, the contourites are believed to form a good analogue for interpretation of how past deep water masses and ocean circulation varied between glacial and greenhouse climates.

There are fewer papers focussing on magmatism at passive margins, but one looks at magma-rich and magma-poor passive margins and shows that calculation of a magma budget is difficult, as the mechanisms involved in lithospheric break-up are similar in both margin types. The authors propose that it is in fact the timing of decompression melting relative to the onset of crustal thinning that is more critical than the overall magma budget.

Overall, this is an interesting collection of papers covering a wide range of features of passive margins and describing many of the techniques used to study them.

— Louisa Perryman, OU Earth Science Student

Book Review

Childs, C., Holdsworth , R. E., Jackson, C. A.-L., Manzocchi , T., Walsh, J. J., and Yielding, G. (eds) 2017. *The Geometry and Growth of Normal Faults*. London: Geological Society Special Publication 439 (ISBN 978-1-86239-967-9; 540pp; hardback £120)

***From the publisher**: This volume will be of interest to those wishing to develop a better understanding of the structural geological aspects of faulting, from postgraduate students to those working in industry. Normal faults are the primary structures that accommodate extension of the brittle crust. This volume provides an up-to-date overview of current research into the geometry and growth of normal faults. The 23 research papers present the findings of outcrop and subsurface studies of the geometrical evolution of faults from a number of basins worldwide, complemented by analogue and numerical modelling studies of fundamental aspects of fault kinematics. The topics addressed include how fault length changes with displacement, how faults interact with one another, the controls of previous structure on fault evolution and the nature and origin of fault-related folding.*

Some of the content of this book will be familiar to Open University students who studied S338, and in particular Block 3, on Basin Analysis Techniques. Many current researchers will be disappointed by the paucity of regional case histories, such as the Basin and Range Province of the USA, Atlantic margin basins in Brazil and west Africa, and the north-west shelf of Australia. Industry specialists may comment adversely on the lack of high-quality seismic imaging and borehole scanning techniques, which are now widely used. There is a total absence of drone and satellite imagery of inaccessible cliff sections to construct panoramic panels.

The book is constrained by the format used in these Geological Society Special Publications, and would lend itself to an A4 (or larger) landscape publication. The approach used by the journal GeoExpro with fold-out diagrams to show basin-wide structures is a chance missed. Some of the diagrams and colour photographs are so small as to be of limited utility. Black and white seismic sections and interpretation panels, such as the ones from New Zealand, are barely usable.

Many of us working in this field are daily using visualisation theatres with headsets and total immersive environments to interpret integrated datasets, and to apply the findings of augmented reality and machine learning. So, a chance missed. But a later edition might benefit from a CD/DVD to show 3D or 4D animations of this rapidly evolving field.

— Amy Bouma, Laverne Broussard, James Ying and Camilla Zinovieff (modified from an earlier review by Tony Grindrod)

Zealandia Te Riu-a-Māui: lifting the long white cloud

Dilys Harlow

Zealandia is Earth's eighth continent. Its presence was announced in 2017, and its name was coined in 1995. But the concept of this continent had been around some time, awaiting geological proof. Zealandia is the collective name for the islands of New Zealand and New Caledonia, plus a few smaller islands, together with the Campbell Plateau, the Chatham Rise, the Lord Howe Rise and themNew Caledonia Trough, a total of 4.9Mkm^2; 94% of the landmass is below sea level and 90% is continental slope. It is Earth's youngest, thinnest and most submerged continent, spanning two tectonic plates (Fig. 1).

There is no international committee to decide what is or is not a continent, but Zealandia meets the criteria commonly applied:

• a major landmass including dry land and continental shelf (Fig. 2)
• a greater elevation than the oceanic crust — Zealandia stands higher than the surrounding oceanic crust, with a modal elevation of –1,100m compared to the ocean floor at *c.* –3,000m.
• a broad range of silicaceous igneous, metamorphic and sedimentary rocks — Zealandia's basement rocks appear to be entirely continental, with Palaeozoic and Mesozoic greywacke, gneiss, schist, granite and many other silicaceous rocks. Orogenic belts such as the Median Tectonic Zone (Median Batholith) and the Haast Schist can be traced across the continent. Above this basement lies a continent-wide unconformity representing extension and rifting from Gondwana *c.* 85Ma, followed by erosion. The proofs come from on-land New Zealand, many island outcrops, zenoliths, drill cores and seabed dredge samples (Fig. 3, *overleaf*).
• a thicker crust with a seismic velocity lower than that of oceanic crust — crustal thickness varies from 10km to 40km, compared to < 7km for oceanic crust; P wave velocity is < 7.0km^{-1} (oceanic crust 7.5km^{-1})
• well defined limits and more than 1Mkm^2 of area — Zealandia is 4.9Mkm^2, two-thirds the size of Australia. It is separated from Australia and Antarctica by oceanic crust.

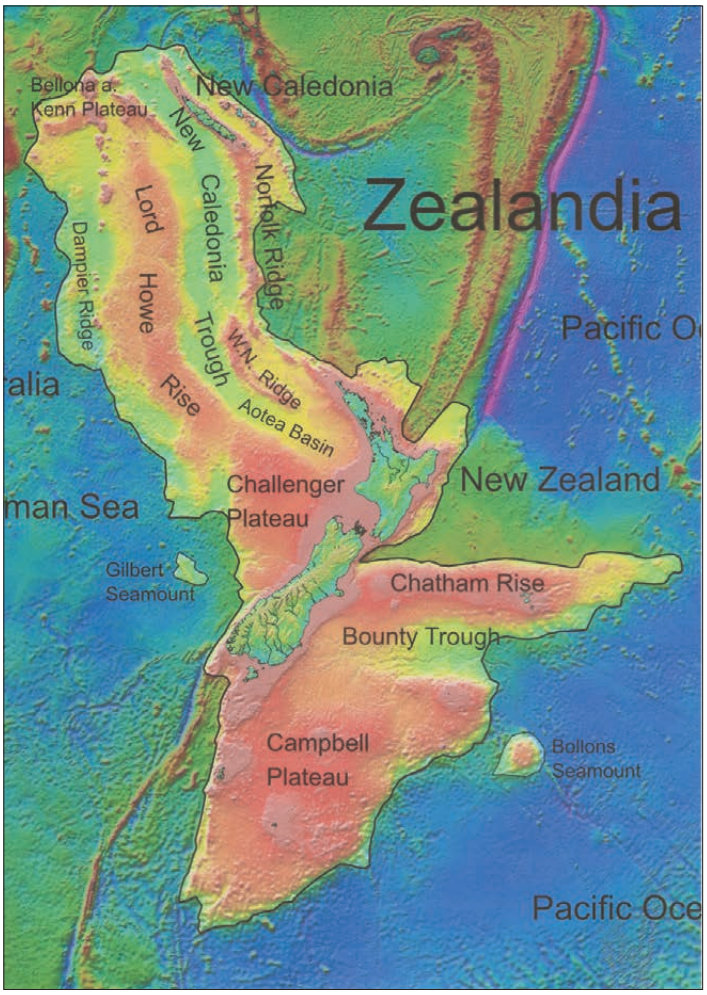


Figure 1 Bathymetric map of Zealandia. Correcting for slip on the Alpine fault the following structures are continuous across Zealandia: The Lord Howe Rise and the Campbell Plateau, the New Caladonia Trough and the Bounty Trench, and the Norfolk Ridge and the Chatham Rise. Depths below sea level: plum 0–1,000m; red 1,000–2,000m; green 2,000–3,000m; light blue 3,000–4,000m; dark blue 4,000–5,000m (image from Mortimer et al. *2014, published with permission from* GSA Today*).*

The origins of Zealandia

The creation of the continent of Zealandia is a result of one of the largest and longest-lived accretionary orogenies known on Earth, which stretched for > 7,000km along the south-east margin of Gondwana from 550Ma to the late Early Cretaceous (Fig. 4, *overleaf*).

An unknown but huge area of the Panthalassa oceanic crust must have been subducted westwards and many continental fragments, island arcs, accretionary wedges, dismembered ophiolites, back arcs, sedimentary basins, and even oceanic plateaus and spreading ridges were accreted, probably obliquely, as terranes onto the Gondwana margin. These crustal additions created Zealandia and augmented the continents of Antarctica, Australia and South America. The accreted material was also intruded and thickened by volcanicity and batholith formation in an Andean-style volcanic mountain chain inland of the subduction zone (Fig. 5, *page 47*).

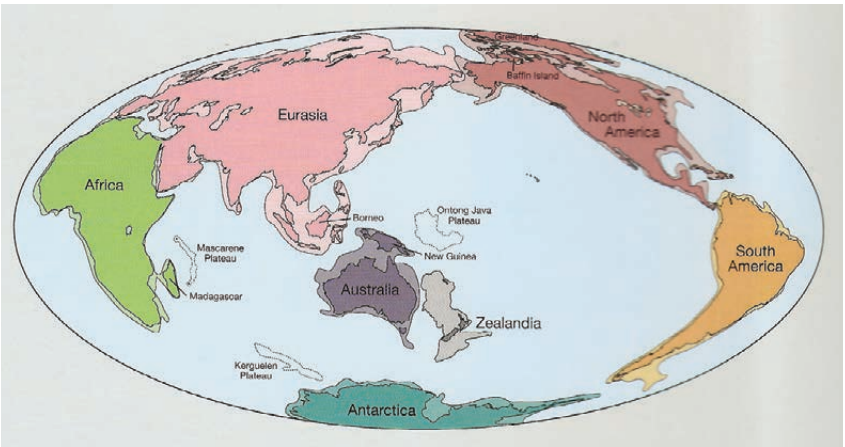


Figure 2 Earth's eight continents (Africa, Antarctica, Asia, Australia, Europe, North America, South America and Zealandia) with their continental shelves; also some large oceanic plateaux and microcontinents — Hammer equal area projection (Nick Mortimer/GNS Science; image from Mortimer et al. *2014, published with permission from* GSA Today*).*

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Figure 3 The geology of Zealandia: NC—New Caledonia; WTP—West Torres Plateau; CT—Cato Trough; Cf— Chesterfield Islands; L—Lord Howe Island; N—Norfolk Island; K—Kermadec Islands; Ch—Chatham Islands; B—Bounty Islands; An—Antipodes Islands; Au—Auckland Islands; Ca—Campbell Island. The Median Batholith and the Haast Schist have been separated by slip on the Alpine Fault (published with permission from GSA Today*).*

forced the Southern Alps upwards for the past 25Ma and has shifted the western side of Zealandia 500km to the north with respect to the eastern side (Fig. 7, *opposite*).

Zealandia, the Pacific Ring of Fire and a novel hypothesis to explain subduction

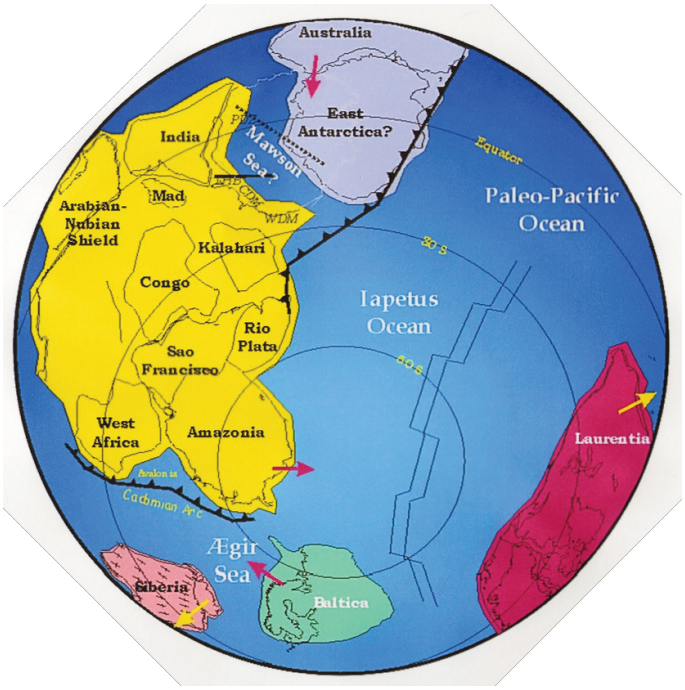
The findings of the International Ocean Discovery Program Expedition 371, published in *Geology* (Sutherland *et al.* 2020) demonstrate dramatic elevation changes over northern Zealandia between 50Ma and 35Ma. Fossils in the drill cores indicate that the Lord Howe Rise, previously below 1km of water, rose up to sea level, while the New Caledonia Trough sank by the same amount, following which the whole of Zealandia subsided a further kilometre deep. These events occurred at the same time (geologically speaking) as widespread changes in mid-ocean ridge orientations, tectonic plate motion speeds and directions, the bend in the Emperor-Hawaii seamount chain and the almost simultaneous formation of the Ring of Fire encircling 10,000km of the western Pacific Ocean.

The isolation of Zealandia

Subduction along the south-east Gondwana margin ceased *c.* 105Ma. The exact cause is unknown, but could have been the impingement of either a spreading ridge or the Hikurangi Plateau (a fragment from the Ontong Java LIP) with the subduction zone. From 105Ma to 85Ma extension started to rip south-east Gondwana apart, possibly as a result of either Pacific slab break-off, orogenic collapse or mid-Cretaceous super-plume activity. Seafloor spreading had started in the Tasman Sea between Australia and Zealandia by 85Ma, and then later in the Southern Ocean between Antarctica, Zealandia and Australia. Once sediment supply from Gondwana stopped and erosion set in, an unconformity developed across Zealandia (Fig. 6, *opposite*).

The stretched and thinned crust slowly cooled and subsided until most, if not all, was submerged by 23Ma. That process might have been the end of the story, leaving either an entirely submerged continent or a sparse archipelago. But tectonic forces intervened to forge the enigmatic Pacific Ring of Fire and to re-model Zealandia. As a consequence of these forces, the convergent boundary between the Indo-Australian and Pacific Plates now bisects Zealandia and the islands of New Zealand, with subduction directed westward in the north and eastward in the south, and the strike-slip Alpine Fault connecting the two regions. Transpression across this fault has

Figure 4 A reconstruction showing the final stages of the assembly of Gondwana 550Ma, including the long south-east Gondwana subduction zone that gave rise to Zealandia (Wikipedia, public domain).



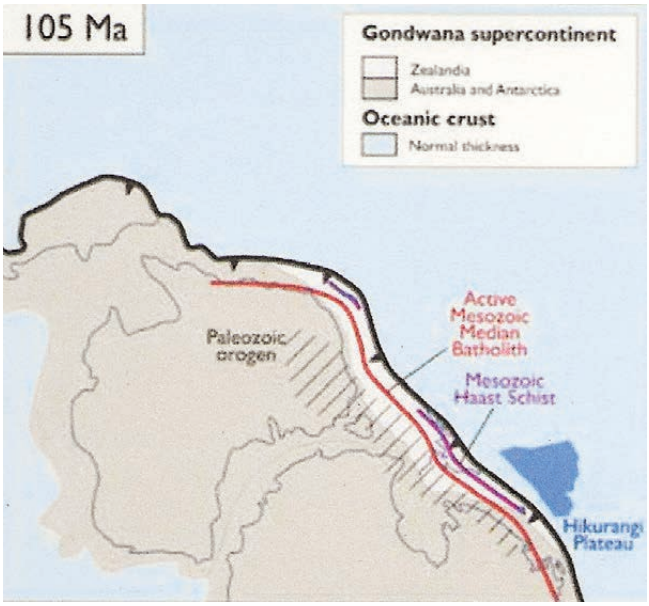


Figure 5 A diagram showing the situation 105Ma as subduction was ending, with the Hikuragi Plateau about to impinge on the subduction zone (image from Mortime, et al. *2014, published with permission from* GSA Today*).*

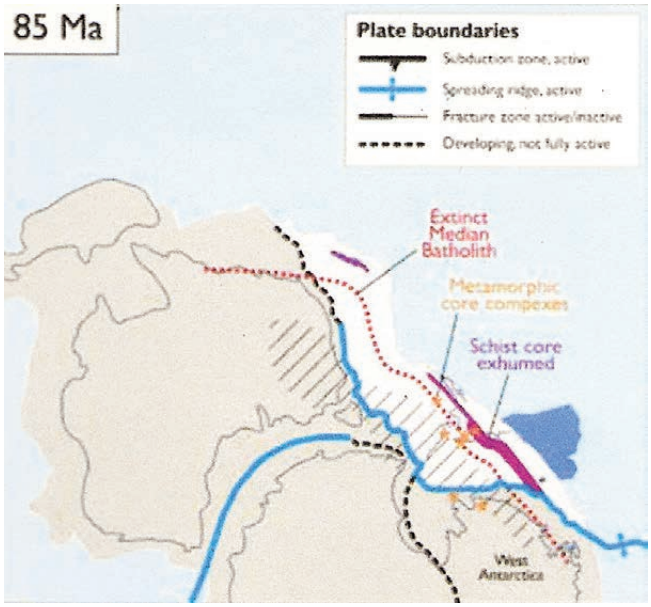
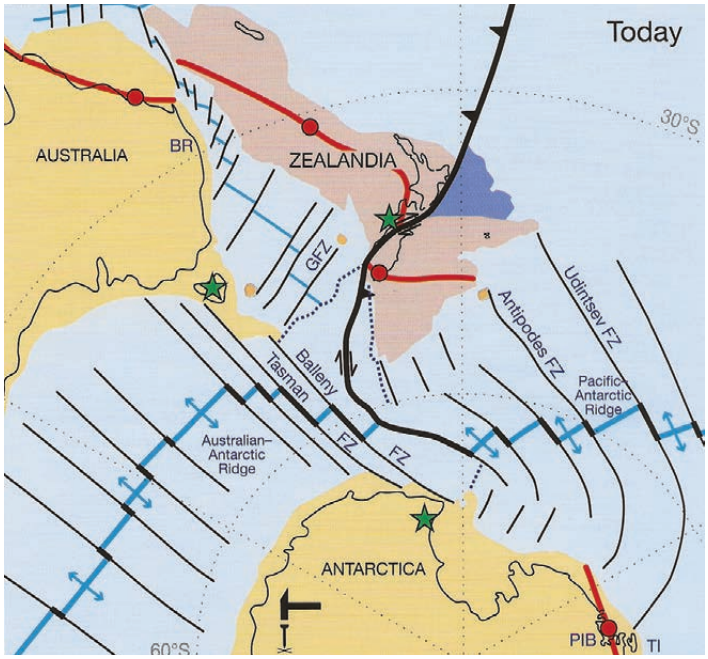


Figure 6 The start of sea-floor spreading and the break-up of Gondwana (image from Mortimer et al. *2014, published with permission from* GSA Today*).*

Sutherland *et al.* (2020) suggest a new mechanism to explain all these changes and how subduction started and spread so rapidly. They hypothesise a 'subduction rupture event' in which locally induced movement set off slip on a fault, which then propagated laterally 'like a massive, super-slow earthquake and resurrected ancient, inactive subduction faults — perhaps like a huge zip-fastener unzipping in stages.

> *"We suggest [that] these elevation changes resulted from crustal delamination and mantle flow that led to slab formation. We propose a 'subduction resurrection' model in which (1) a subduction event activated lithospheric-scale faults across a broad region during less than ~5m.y., and (2) tectonic forces evolved over a further 4–8m.y. as subducted slabs grew in size and drove plate-motion change. Such a subduction rupture event may have involved nucleation and lateral propagation of slip-weakening rupture along an interconnected set of pre-existing weaknesses adjacent to density anomalies."*



The authors go on to express the hope that Zealandia's sedimentary record will further help to clarify these earth-changing events.

All of this new evidence shows that Zealandia is a unique and important new continent, with much still to reveal; and that the geological history of the Gondwana supercontinent is incomplete and misleading if Zealandia is ignored and omitted.

(This article is based on a lecture by Dilys Harlow to the Severnside Branch AGM 2020; originally published in Sabrina Times, *OUGS Severnside Branch, May 2020, 2–6 — Ed.)*

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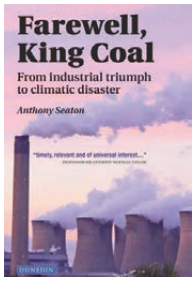
Figure 7 The situation today, showing the spreading ridges and oceanic fracture lines indicating where the three continents originally touched each other: green stars are Jurassic dolerites; red circles and lines show Mesozoic I-type granites. Spreading ended in the Tasman Sea c. *50Ma (Nick Mortimer/GNS Science, published with permission).*

Book review



Seaton, Anthony 2018 *Farewell, King Coal: From industrial triumph to climate disaster*. Edinburgh: Dunedin Academic Press (ISBN 978-1-780-46077-2; I–xvi + 231pp; hardback £24.99

The strap line on the cover "From industrial triumph to climate catastrophe" is a fair summation of the scope of the book, but the text is not primarily about the role of coal in climate change. The main subject matter covered in two-thirds of the text is the impact of coal on the health of individuals working in all aspects of the coal industry, from miners at the face to those engaged in handling coal at the surface. The epidemiological implication on population health is also considered again in context primarily of coal, but in the latter part of the book of its usurper, 'King Oil'.

The author presents the text as a history of coal use particularly once it became widespread across the UK in the 17th century and from his own perspective having worked most of his professional career in medical capacities with those from the coal industry.

At the heart of the text is an apparently simple question: "Does working in the coal industry cause harm?". In some respects that was a simple question to answer, as clearly fires, explosions and accidents with machinery have readily quantifiable outcomes. However, fixating on those causes overshadowed the more complex question of potential harm caused by long-term exposure to dust and chemical derivatives. Nevertheless ,these related enquiries would still seem to demand simple answers, given on the one hand the observable effects both in X-Ray images and at autopsy on the lungs of coal workers, and on the other hand increasing incidences of tumours caused by direct contact. However, given the plethora of complicating factors from tuberculosis to cigarette-smoking and the apparent lack of direct links to ill health, these questions were only answered by medical and scientific professionals working in the UK as the country's coal industry finally drew to a close.

In the early 20th century, at the peak of coal use in the UK approximately, 1.25 million workers were employed in some capacity in the industry; but by 1980 that number had dwindled to *c.* 250,000 (figures derived from the text). I recall clearly the daily television news footage of the 1984 Miner's Strike, and the account given by the author — as an invested yet impartial observer with intimate familiarity with the industry on the motives and machinations — is intriguing. Yet while the costs associated with deep extraction were a factor, so too was the emerging recognition that coal dust exposure did cause ill health and the additional burdens that placed on the industry.

In extending the assessment to the pathological effects of pollution and physical exposure to 'King Oil', I was engaged at a personal level. Growing up in a rural setting and taking seasonal jobs on farms, I was never affected by 'hay fever', despite hours loading bales by hand into confined and very dusty barns. Within a year of moving to Birmingham I was affected; a circumstance that continued when I moved to Bristol. Bristol occupies a hollow in the landscape and on a windless day approaching the city over the hills from the north a brown haze over the city is clear to see. Moving occupations again I relocated to the south coast of Devon, and despite again finding myself in and around farms and dusty barns within a year or two my 'hay fever' had vanished. The text links microscopic combustion pollutants to exacerbation of conditions caused by larger particles, be they coal dust, microbes or general dust and pollen; perhaps that fact has a bearing on my own experience. It is perhaps a further illustration of the far-reaching consequences of coal use in the UK that my father began his professional career surveying the unrecorded coal workings of the Kingswood suburb of Bristol.

The final chapters of the text are dedicated to the impact of fossil fuels on the global climate. This is of course a highly contentious issue and the opening chapter of the section details the known and observable effects of fossil fuel use since about the mid-19th century. Thereafter, the text considers the probable role fossil fuel use has had on the environment, carefully setting predictions against observed outcomes. As these often do not tally, the author makes the valid argument that while an individual prediction may not be exactly borne out by observable events, it does not, however, follow that the underlying premise is invalid if broadly supported by evidence.

The book concludes by taking the view that global climate change is occurring, and that current scientific understanding indicates that fossil fuel use is a contributor, and poses the questions: "What can governments do?", and, "What can individuals do?". While the author's opinions align broadly with my own, I felt it unlikely that those with opposing opinions would be persuaded.

The text is well presented with abundant clearly laid out figures and photographs, and printed on quality gloss paper it is a pleasure to read. It may, however, be challenging to those unfamiliar with the style of medical-scientific journals, as the text relies heavily on acronyms: CWP, COPD, PMF, etc. While each is introduced at first use — Coal Workers' Pneumoconiosis (CWP) for example — and appears in the glossary, at a certain point I found it helpful to write some on a bookmark. I maintain, however, that the text is first and foremost an engaging and readily approachable account of the elucidation of health effects primarily on coal workers, but that the section on the climate does not add weight to the complicated and contentious nature of the debate.

— Chris Popham, OUGS South West Branch Organiser

From fossils to family

Gilliam Michaels

Introduction

In early March 2020, I visited Tanzania for a fortnight's bird-watching. Travelling from Kilimanjaro to the Serengeti, our group focused almost entirely on the rich diversity of birds and mammals in this spectacular region. But there was time to notice some of the most obvious geology, particularly the volcanoes and escarpments of the Rift Valley. We even spent a couple of hours at the Oldupai Gorge Museum, which celebrates the palaeontological discoveries of the Leakey family and others. (Oldupai is now the preferred spelling, more similar to the Maasai pronunciation than 'Olduvai'. The name means 'place of wild sisal', a plant abundant in the area). The Oldupai River basin holds a continuous record of nearly two million years of hominin* occupation. On my return home, I studied the geology I had seen and the latest research on human evolution.

Geology of northern Tanzania

Oldupai Gorge is a deep ravine in a rift platform of the Gregory Rift, the Eyasi half-graben, on the eastern edge of the Serengeti Plain and at the foot of the Ngorongoro Highlands (Fig. 1). The area demonstrates the major features of East African geology: Precambrian basement rocks, regional plateaux and on-going rifting (Scoon 2018).

The East African basement rocks are the greenstones and granite-gneiss plutons of the Archaean Tanzanian craton, and to its east the Neoproterozoic Mozambique Belt (Scoon 2018, Section II.4). This band of quartzite and schist with granite plutons runs from Antarctica to the Middle East, and formed on the closure of an ancient ocean between Madagascar and India. Basement rocks outcrop on the Serengeti Plains as kopjes and as ribbon-like ranges of hills (Fig. 2).

Figure 1 Map of Oldupai and the surrounding region (copied from Mollel and Swisher 2012, fig. 1; used under CC BY-NC-ND license).

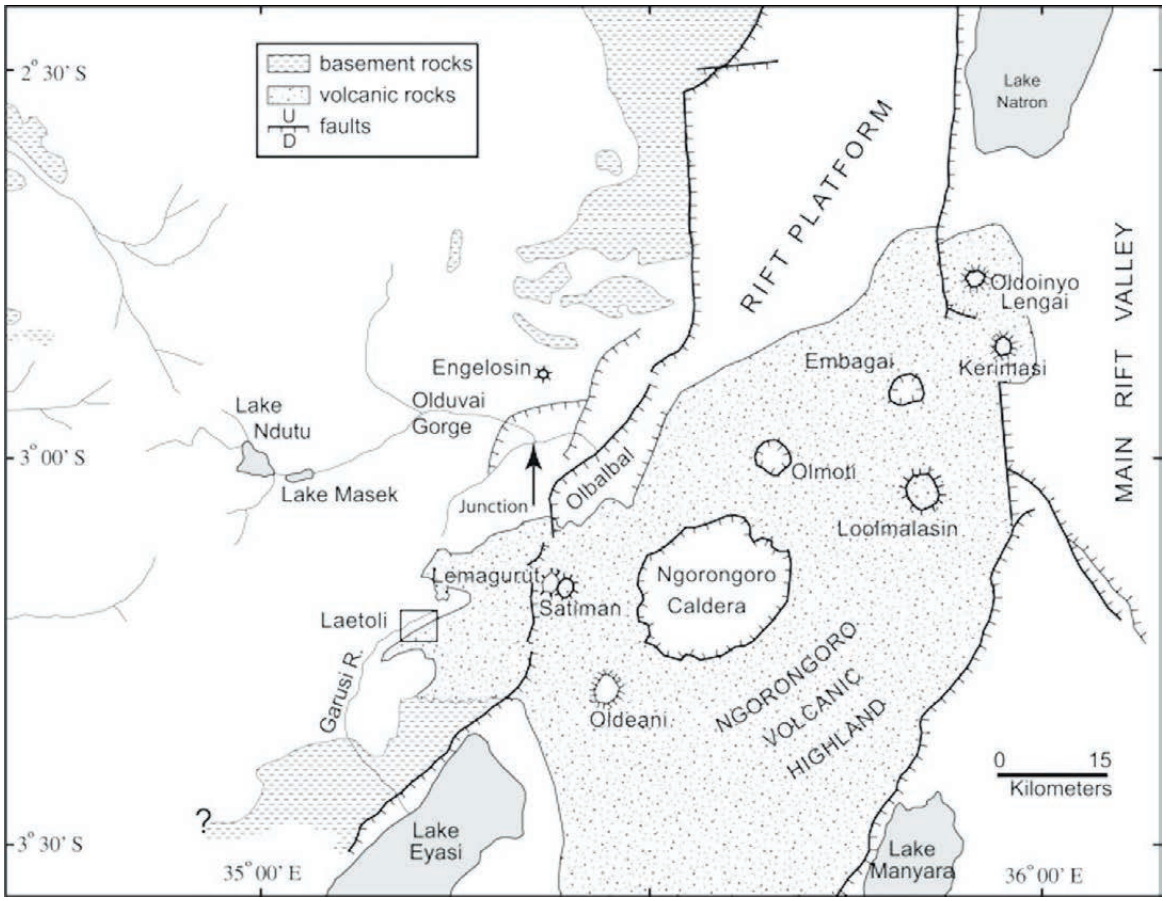


Figure 2 An outcrop of Precambrian basement rock looms over tourists at the Seronera visitor centre in the Serengeti National Park (photo by G. Michaels).

* Recent genetic studies of great apes have altered our taxonomy and its nomenclature, and the literature is inconsistent in its usage. In this article, the term 'hominin' refers to the human lineage (*Hominini* subtribe) after it split from the chimpanzee lineage. 'Human' refers to the genus *Homo*, and for convenience 'australopithecine' refers to the other genera within the subtribe, not just *Australopithecus.*

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Repeated rifting, collision and uplift during the Neoproterozoic, Palaeozoic and Mesozoic eras produced the East African regional plateaux, including the Serengeti. A particularly severe erosion episode in the late Cretaceous Period created a prominent 70 million-year-old surface, which is found throughout the region. Little material remains from the earlier Mesozoic, or from the Mesoproterozoic and Palaeozoic eras.

The latest rifting process, the East African Rift System, began during the Oligocene Epoch when a large igneous province was emplaced in Ethiopia at the triple junction with the spreading ridges of the Red Sea and the Gulf of Aden (Scoon 2018, Section II.4). Rifting progressed southward, reaching Tanzania in the Miocene, and produced a series of predominantly north–south-trending grabens and half-grabens. As this spreading process continues, the Somali plate is separating from the main Nubian (African) plate.

In Kenya, the rift branches around the Tanzania craton, dividing into the western Albertine Rift and eastern Gregory Rift with Lake Victoria lying in between. The Albertine Rift is more active seismically and contains several large deep freshwater lakes. The Gregory Rift is much shorter, terminating in northern Tanzania. It contains a chain of shallow alkaline lakes, and has more voluminous volcanism than the Albertine Rift. Notable among its volcanoes are Ngorongoro and Oldoinyo Lengai.

Ngorongoro's name is Maasai in origin and said to be onomatopoeic, from the ringing of cow bells. The Ngorongoro Volcanic Highlands include a group of extinct volcanoes, of which Ngorongoro is the largest (Scoon 2018, section III.10). Its original height is estimated to have been 5–6km, but two major eruptions *c*. 2.2Ma and *c*. 2.0Ma caused its cone to collapse, leaving the largest intact, unfilled caldera in the world. The caldera measures *c*. 22km ¥ 18km, and contains freshwater springs and an alkaline lake. It is renowned not only for its geological features but also for its spectacular wildlife (Fig. 3).

Oldoinyo Lengai ('Mountain of God' in Maasai) is the most active volcano in the Gregory Rift (Scoon 2018, section III.17). Its last severe eruption was in 1996–7, and its most recent in 2013. It is bimodal, generating two immiscible melts; and it is the only active volcano in the world producing alkali carbonatite lava. The more abundant magma is alkaline silicate. Alkali carbonatite lava causes explosive eruptions, and ash dating back to 1.37Ma is widely dispersed in the area. Natrocarbonatite lava began to appear *c*. 1,250 years ago. It has an unusually low eruption temperature (< 600°C) and very low viscosity, so its effusive eruptions solidify quickly, forming unusually thin flows. These are typically pale grey, because the natrocarbonatite readily oxidises in water to light-coloured secondary minerals.

Oldupai Gorge

The oldest strata so far examined at Oldupai date to 2.4Ma, and show evidence of a freshwater lake in a savannah environment (Stanistreet *et al.* 2020). The formation was found in deep boreholes drilled around the Naibor Soit hill, a Mozambique Belt quartzite inselberg, for which it is named (Fig. 4 *opposite*). From 2.2Ma to 2.0Ma these sedimentary strata were interwoven with volcanic material from Ngorongoro's major eruptions and collapse. The last massive eruption completely covered the freshwater lake with a 7m thick layer of ignimbrite.

Above this comes the Oldupai Group (Scoon 2018, section III.11). It consists of seven predominantly sedimentary beds containing reworked volcaniclastic material, sandstones, limestones and tufa (Fig. 5, *opposite*). Several tephra deposits from nearby volcanoes enable precise dating. Detailed fieldwork suggests that the site had become an alkaline playa lake, with nearby freshwater springs, which provided a suitable environment for hominins to settle (Ashley *et al*. 2010). The group is covered by ash, mainly from Oldoinyo Lengai.

Figure 3 Ngorongoro caldera from the viewing point (photo by G. Michaels).

Figure 4 Panorama of Oldupai Gorge. The red monolith in the foreground is part of Bed III, named 'The Castle'. In the distance are the twin peaks of Naibor Soit (photo by G. Michaels).

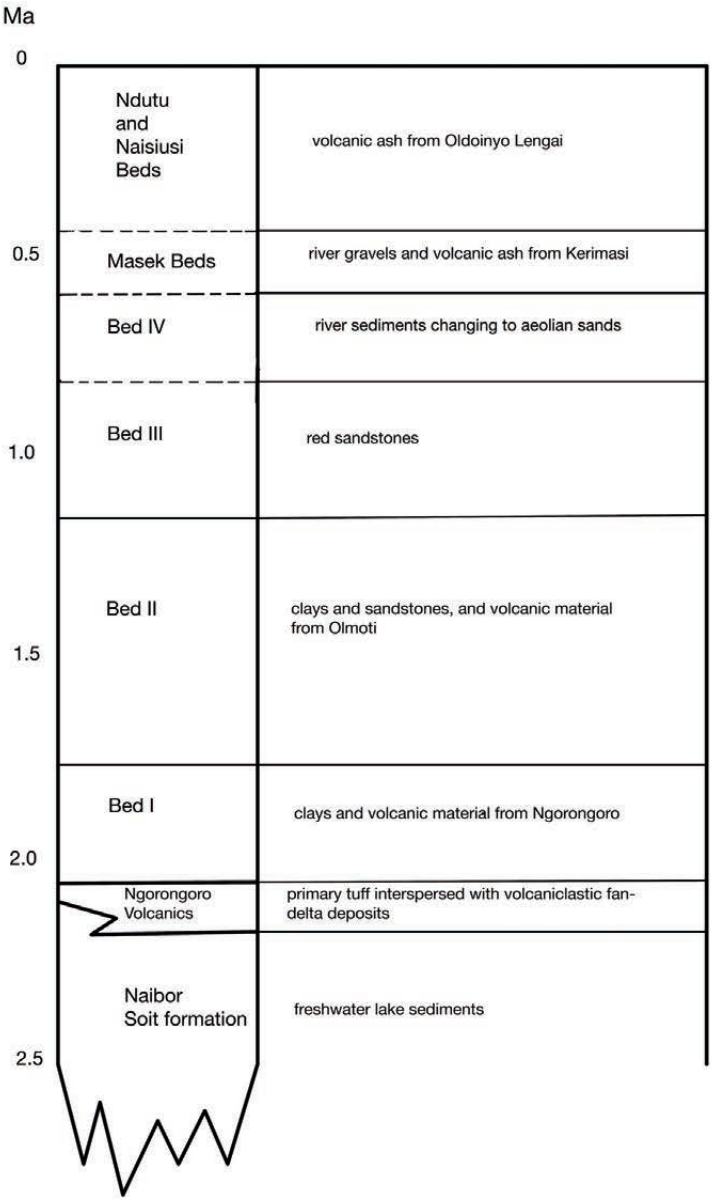

Figure 5 Oldupai stratigraphic column (adapted by G. Michaels from Stanistreet et al. *2020 fig. 2 and from Scoon 2018 Section III.11).*

Palaeontological fieldwork began in the early 20th century, but it was the mid-century discoveries of the Leakey family that brought the site to popular attention (Scoon 2018 Section III.11.3). The earliest major fossil finds, dating to 1.8Ma, were in Bed I: *Paranthropus boisei* (otherwise placed in the genera *Zinjanthropus* or *Australopithecus*; Fig. 6, *overleaf*) and *Homo habilis*. Remains of *Homo erectus* found in Bed II date to 1.2Ma. The earliest evidence of *Homo sapiens* dates to *c.* 70,000 years ago, much later than in other parts of Africa.

As well as fossils, the site is rich in stone tools, mostly made of quartzite and lava (Key *et al.* 2020). *H. erectus* also used chert, but these tools are found in only one part of Bed II. The earliest tools are considered to be the work of *H. habilis*. They were made by striking a core stone with a hammerstone to produce flakes: the Oldowan toolkit. Later hominins such as *H. erectus* also made handaxes by shaping the edges of large flakes; these make up the Acheulean toolkit. Bed II at Oldupai is one of few sites to show this advance in technology as a continuous record. About 300,000 years ago, a further advance suggests increased intelligence and dexterity. In this development — called the prepared-core technique — the core stone was deliberately shaped so that a carefully placed single strike produced a flake of planned size and shape. The resulting tools made from these flakes were much more diverse in structure and utility than the earlier toolkits.

Human evolution

The Oldupai Gorge Museum displays many of the tools found at the site. It also has replicas of the hominin fossils found at Oldupai and elsewhere in East Africa in reconstructed model skeletons. These include 'Lucy', the 3.2Ma female *Australopithecus afarensis* from Ethiopia, and a cast of the 3.7Ma bipedal footprints found at Laetoli, near Oldupai, which are thought to have been made by the same species (Fig. 7, *overleaf*). The exhibits include an account of human evolution, but this is brief and simplified, and omits many of the discoveries made elsewhere in Africa, and in Europe and Asia.

Figure 6 Reconstruction of Paranthropus boisei *(Smithsonian Institution 2020; https://humanorigins.si.edu/evidence/human-fossils/species/paranthropus-boisei; reconstruction © John Gurche).*

Human evolution, 1990s style Hominin fossils are sparse and fragmentary, but by the end of last century the discoveries in Africa, Europe and Asia had led to a fairly straightforward narrative of human evolution (Sheldon and Spicer 2001, 121–3). According to this account, the last common ancestor of humans and chimpanzees was a quadruped living in African forests during the Miocene Epoch, *c.* 7–10Ma. As the climate cooled and dried, forests gave way to grassland. The chimpanzee and human lineages diverged, and a species of hominin moved on to the savannah. It differed from its predecessors in its dentition and in being bipedal, shown by its craniovertebral and pelvic structures. This was a gracile australopithecine, *Australopithecus amanensis*, a precursor of *Au. afarensis* (Lucy). Between 3Ma and 2Ma, two new forms of hominin evolved: the 'robust australopithecines', *Paranthropus*, of which P. boisei was an example, and early humans, including *Homo habilis*. Both groups of australopithecines became extinct by 1Ma.

H. habilis was succeeded by *H. erectus*, the first hominin to leave Africa, *c.* 2Ma. *H. erectus* settled widely in Eurasia, a migration termed the 'Out-of-Africa I hypothesis'. Later human species also arose in Africa and some of these groups also migrated into Eurasia. One of these, *H. heidelbergensis*, evolved in Europe to *H. neanderthalensis*, *c.* 400,000 years ago.

* The human species is taxonomically spelled *Homo neanderthalensis*, as its established Linnaean nomenclature. The generic spelling is 'Neandertal', after the German spelling of the Neander Valley and the type-site — Ed.

Figure 7 Reconstruction of formation of Laetoli footprint trail by Australopithecus afarensis *(© Smithsonian Institution 2020; https://humanorigins.si.edu/evidence/behavior/footprints/laetoli-footprint-trails).*

H. sapiens appeared *c.* 200,000 years ago in East Africa, possibly having evolved as a direct descendant of the *H. heidelbergensis* population that had remained there. Neandertal* anatomical features evolved long before its cognitive abilities. A major advance in cultural development *c.* 60,000 years ago triggered a second migration of some groups into Eurasia, called the 'Out-of-Africa II hypothesis'. *H. sapiens*' greater intelligence and tool-making skills enabled them to replace archaic humans throughout their ranges by *c.* 30,000 years ago.

This story of human evolution describes a linear progression of changes in anatomy and culture. Limb-length ratios changed (arms became proportionally shorter, legs longer). Cranial volume increased from *c.* 300–500ml (comparable to modern chimpanzees) to 1200–1400ml (as in modern humans). Skulls became more spherical in shape. Height increased, while the difference in height between the sexes decreased. Facial changes included more delicate features with flatter faces, with more defined chins. Adaptations in dentition are helpful taxonomic indicators. Stone tool-making technology demonstrates increasing manual dexterity and foresight.

But new discoveries and investigative techniques show that the history of human evolution is much more complicated than this brief account, and there are still many unanswered questions.

Human evolution, 2020 Major revisions in the story of human evolution include the date when the hominin and chimpanzee lineages diverged, the variety of forms early humans took, and the extent to which interbreeding occurred. Features of modern humans appeared much earlier than previously recognised, and some features of archaic humans persisted for much longer, into the late Pleistocene. There is still strong evidence that modern humans originated in Africa, but not in a single region as a linear step. Rather, it was the result of many small populations throughout the continent, with different phenotypes moving throughout

the continent and occasionally meeting and interbreeding. Eventually population bottlenecks reduced diversity and resulted in a more uniform phenotype.

The chimpanzee/human divide

Evidence for the evolution of early hominins has been summarised by Barras (2017) and by Levin (2015). Molecular clock dating suggests that the last common ancestor (LCA) of chimpanzees and humans lived well before 5Ma, but the actual date is imprecise, as the rate of genetic mutation is unclear. However, new fossil evidence suggests that the divergence occurred by the late Miocene. A skull dated 7Ma from Chad, *Sahelanthropus tchadensis*, has mixed ape-like and humanoid characters: a small brain, ape-like cranium and upper face, but humanoid middle face and dentition (Fig. 8). The position of the foramen magnum (through which the spinal cord descends from the brain) shows that it stood upright. It is thought to be close to the chimpanzee–hominin LCA, possibly *the* LCA itself or the earliest true hominin.

Another hominin, *Orrorin tugensis*, lived *c*. 6Ma in Kenya. Its dentition had some similarities to that of modern humans. Its femoral structure suggests that it might have been bipedal, but its arms and hands appear to be adapted for tree-climbing. This would contradict the theory that bipedalism developed because hominins left the forest for savannah, although it is consistent with the locomotion of modern non-human great apes, which occasionally stand on two feet. Other fossils from Ethiopia: *Ardipithecus kadabba* and *Ar. ramidus*, dated *c*. 5.8Ma and 4.4Ma respectively, might also have been bipedal, but arboreal. Their sparse remains include dentition that is predominantly ape-like, but with some modern features, particularly in *Ar. ramidus*.

Figure 8 Reconstruction of Sahelanthropus tchadensis *(Smithsonian Institution 2020; https://humanorigins.si.edu/evidence/human-fosils/species/sahelanthropus-tchadensis; reconstruction © John Gurche).*

Figure 9 Reconstruction of Australopithecus afarensis *(Smithsonian Institution 2020; https://humanorigins.si.edu/evidence/human-fosils/species/australopithecus-afarensis; reconstruction © John Gurche).*

The *Australopithecus* line possibly evolved directly from *Ardipithecus*. *Au. afarensis* was once believed to be the only hominin in East Africa during the Pliocene, and the direct ancestor of both the *Homo* and the *Paranthropus* genera (Fig. 9). However, the discovery of *Kenyanthropus platyops* at Lake Turkana, Kenya in 1999 further complicated the story. Dated *c*. 3.5–3.0Ma, it had a flat face and a relatively spherical skull, more like a modern human than an australopithecine. It might also have used stone tools, as tools from the same date-range were discovered near by. This species has also been proposed as the ancestor of the human lineage, and *Australopithecus* relegated to a 'sister taxon' (any taxa derived from a common ancestral node); however, *K. platyops* is known only by the find of a single skull, and it is damaged; its validity as a separate species has therefore been questioned.

During from the next two or three million years, several other fossils have transitional forms, with different combinations of australopithecine and humanoid anatomical features. These include *Au. sediba*, a 2Ma fossil from South Africa, with some *Homo-like* facial features, dentition and pelvis, but with a cranium and most of its body more australopithecine-like. The variety of dissimilar but contemporaneous specimens shows that the evolution of early humans was not linear, but rather evolved from different characteristics appearing in different combinations over a long period of time. It also illustrates the difficulty in ascribing fragmented fossils to different species, when an individual has both 'modern' and 'archaic' skeletal anatomy. In any case the species concept is itself often problematic when applied to evolutionary lineages.

Out of Africa — but when?

All of the species mentioned so far, except *H. neanderthalensis*, originated in Africa. According to the Out-of-Africa I hypothesis, the only hominin outside Africa by the Pleistocene was *H. erectus*, which had evolved sufficient intelligence (inferred

Figure 10 Reconstruction of Homo erectus *(Smithsonian Institution 2020; https://humanorigins.si.edu/evidence/human-fossils/species/homo-erectus; reconstruction © John Gurche).*

from its cranial volume, *c*. 1,000ml) to make its way into Eurasia (Fig. 10). But fossils found in Dmanisi, Georgia, dated 1.85Ma, may contradict this hypothesis (Lordkipanidze *et al*. 2013). The Dmanisi fossil skull has a cranial volume of *c*. 600ml, and the face is distinctly archaic, with a protruding middle face but a receding chin. Different researchers propose that the Dmanisi fossils are *H. habilis*, or an early subspecies of *H. erectus*, or a new species, altogether, named *H. georgicus*. However these bones are classified, they indicate either that small-brained hominins migrated from Africa to the Caucasus, or that they evolved from larger-brained hominins who had made the journey. It is implausible that evolutionary pressures would lead to marked loss of brain volume, but hybridisation between different species can have this effect. Hybrid primates and other mammals are often not intermediate in appearance compared to their parents, but exhibit considerable variation in phenotype, including significant size differences, pronounced facial changes and dental anomalies (Martinón-Torres *et al.* 2017).

And hybridisation between *H. erectus* and another species might explain the dwarf hominin, called the 'hobbit', on Flores Island, Indonesia (Fig. 11). *H. floresiensis* lived *c*. 100,000–50,000 years ago, but had the small brain and body size of australopithecines (Lawton 2019). A similar species (*H. luzonensis*) lived *c*. 67,000–50,000 years ago on the island of Luzon, the Philippines, *c*. 3,000km south of Flores (Détroit *et al.* 2019). Suggestions that various chromosomal defects or metabolic disorders caused this dwarfism in both species are not borne out by detailed pathological examination of the fossils (Baab *et al.* 2013). Another possible explanation for these species is 'island dwarfism' — some mammals in isolated populations evolve into smaller forms; but brain volume is usually conserved in these cases. The anatomy of *H. floresiensis* suggests that it might be a late descendant of a previously unknown early hominin, a sister taxon and contemporary of *H. habilis*, which itself might have migrated out of Africa before *H. erectus* (Argue *et al.* 2017). But although brain volume is only loosely correlated with intelligence, it is difficult to imagine how such small-brained hominins could have deliberately sailed to these south-western Pacific islands.

We were not alone

The Out-of-Africa II hypothesis has also been challenged: *H. sapiens* appears to have left Africa well before 60,000 years ago. Several fossils found in China have been claimed to have mixed features of *H. erectus* and *H. sapiens*, although an alternative view is that they are simply forms of *H. erectus* (Douglas 2018). The oldest so far discovered is a pair of skulls from 300,000 years ago, in Yunxian, central China. A similar skull ('Dali man'), dating to 260,000 years ago, was excavated in Shaanxi, north-west China, and teeth of modern type dated 80–120,000 years old were found in Daoxian, south China. Some palaeontologists have postulated that *H. sapiens* might have evolved in East Asia rather than in Africa. However, genetic evidence strongly suggests that Africa was the continent of origin (Scerri *et al.* 2018).

Older fossils with characteristics of *H. sapiens* do occur in Africa and in the Middle East. For example, skulls found at Jebel Irhoud, Morocco, have modern facial features but elongated crania, an archaic feature. When the first was found, it was carbon-dated to *c*. 40,000 years ago, and assumed to be a relative of the Neandertals. When the site was re-explored, the second skull unearthed, and more deep-time dating methods applied, both skulls were shown to be 315,000 years old (Lawton 2019). These skulls are thought to be early *H. sapiens* or a close relative. Stone tools at the site were of the 'prepared core' type, indicating planning ability. Similar tools from the same period at Olorgesailie,

Figure 11 Reconstruction of Homo floresiensis *(Smithsonian Institution 2020; https://humanorigins.si.edu/evidence/human-fossils/species/homo-floresiensis; reconstruction © John Gurche).*

Kenya, were found with red (ochre) and black (manganese) rock fragments, perhaps prepared for artwork. Human cognitive abilities therefore developed early.

This early development is perhaps demonstrated by another hominin found in South Africa, from at least 300,000 years ago, which had australopithecine-like hips, a small skull like an early *Homo*, and anatomically modern feet; it is classified as *H. naledi*. The fossils were found in a deep and nearly inaccessible cave, which has given rise to speculation that *H. naledi* deliberately placed their dead in the cave, a surprisingly complex behaviour in such a small-brained creature (Dirks *et al.* 2015).

Other groups of fossils with mixtures of modern and archaic features, each different, have been found at various sites in Africa. They are generally considered to be early subspecies of *H. sapiens*, although the Florisbad skull from South Africa (260,000 years old) is sometimes given species status as *H. helmei* (Lawton 2019). Most of these intermediate forms are from the same period, up to *c*. 150,000 years ago. But another group of fossils with mixed archaic and modern characteristics (the 'Red Deer Cave people') has been found in Yunnan Province, China, and dated to a mere 11–14,000 years ago (Ji *et al.* 2016). Other fossils of transitional type from the Democratic Republic of Congo, Kenya and Nigeria may also date from as recently as 14,000 years ago (Lawton 2019).

So the fossil evidence found so far shows that *H. sapiens* evolved much earlier than previously believed. Anatomical and cultural features are reckoned to indicate that our species appeared at least 300,000 years ago, and that populations had begun to migrate out of Africa by at least 120,000 years ago. But several other kinds of hominin species, with a variety of archaic and modern characteristics, co-existed with them almost into the Holocene.

Is the answer in our genes?

Nuclear and mitochondrial DNA can sometimes be extracted from hominin fossils, and compared with modern genomes. The evidence revealed by this process shows that early humans interbred frequently. Modern humans have genetic material from Neandertals, from Denisovans and from other as-yet-unknown ancestors (Veeramah and Hammer 2014).

The only fossils identified so far as Denisovan, from their genomes and dental morphology, are a finger bone and three teeth. These were found in the Denisova cave in the Altai Mountains, southern Siberia, and dated 50–30,000 years ago (Reich *et al.* 2010). Nuclear DNA from these finds shows that Denisovans were more closely related to *H. neanderthalensis* than either taxon were to *H. sapiens*. The last common ancestor of all three groups has not been identified, but probably lived *c*. 600,000 years ago, as estimated from the molecular clock. Fossils found in the Atapuerca mountains, Spain (the 'Sima hominins') are *H. Neanderthalensis* and dated to 430,000 years ago (Lawton 2019). This dating suggests that *H. heidelbergensis* was a 'sister' taxon to the human/Neandertal LCA, not a direct ancestor to both species as was once believed. Soon after the common ancestor of Neandertals and Denisovans diverged from the hunan lineage, the population appears to have undergone a tight bottleneck, after which their lineages split.

H. sapiens also underwent at least one bottleneck episode, which would have reduced its phenotypic diversity. Lawton (2019) mentions that mitochondrial DNA *c*. 1,500 people throughout the world shows that they have a common maternal ancestor ('Mitochondrial Eve'), who lived in Africa *c*. 200,000 years ago. A small sample of Y-chromosomes from around the world suggests that they have a common paternal ancestor ('Y-chromosome Adam') no more than 300,000 years ago (Lawton 2019). In both cases there is a wide confidence interval for the dating, as it depends on how fast the molecular clock is assumed to tick; and both sample sizes are too small to exclude other lineages in modern populations.

Although so little Denisovan skeletal material has been identified so far, their genetic material is widespread, particularly in eastern Eurasia. Neandertals were more common in the west, but their fossils have been found as far east as the Altai Mountains in central Asia (including the Deisova Cave), and their genetic material has also been found in China (Douglas 2018). Fossil DNA shows repeated interbreeding between *H. sapiens*, Neandertals and Denisovans. Fragments of both Denisovan and Neandertal DNA are found in the genomes of modern humans (Guimarães and Silva 2020). But fossil and modern DNA also contains segments from other unidentified hominins (Durvasula and Sankararaman 2020; Teixeira and Cooper 2019).

Therefore, in summary, current evidence suggests that modern humans evolved from a variety of populations with different phenotypes, dispersed throughout Africa, but occasionally meeting and interbreeding over many thousands of years. Population movements would have increased in response to changing environmental conditions in the volatile Plio-Pleistocene climate. Several hominin groups migrated into Eurasia at different times, and continued to evolve, travel and interbreed. Anatomical features of modern humans had appeared by *c.* 300,000 years ago, but various populations with archaic features persisted until the late Pleistocene.

Human evolution, the future

New fossils are still being found, further complicating the story of human evolution.

In November 2019 in Bavaria, Germany, remains of a fossil ape with unique skeletal characteristics were discovered (Fig. 12, *overleaf*). Named *Danuvius guggenmosi*, these fossils have been dated to 11.8Ma (Böhme *et al.* 2019). They were smaller than bonobos ('pygmy' chimpanzees, *Pan paniscus*), with similar limb proportions, but their skeletal morphology was in other ways similar to hominins. The finders suggest that these apes had a previously undescribed form of locomotion, with equal adaptation to bipedalism and to suspension (swinging from branches, as chimpanzees do). This is, so far, the earliest indication of bipedalism. *D. guggenmosi* may have been close to the LCA of chimpanzees and humans.

There is a general assumption that chimpanzees have stayed relatively unchanged since the hominin lineage diverged, apart from the splitting of the common chimpanzee (*Pan troglodytes*) and bonobo lineages *c*. 2Ma. Diogo *et al.* (2917) suggest, on morphological grounds, that the chimpanzee/hominin LCA was similar to modern bonobos. So human evolution is seen as a progression from a chimp-like ancestor to modern humans. But the discovery of *D. guggenmosi* and the ubiquity of 'modern' features in ancient hominins indicate that the characteristics considered diagnostic of modern humans are far older and less specific than had been thought. More research into fossils and genomes of non-human African great apes is needed.

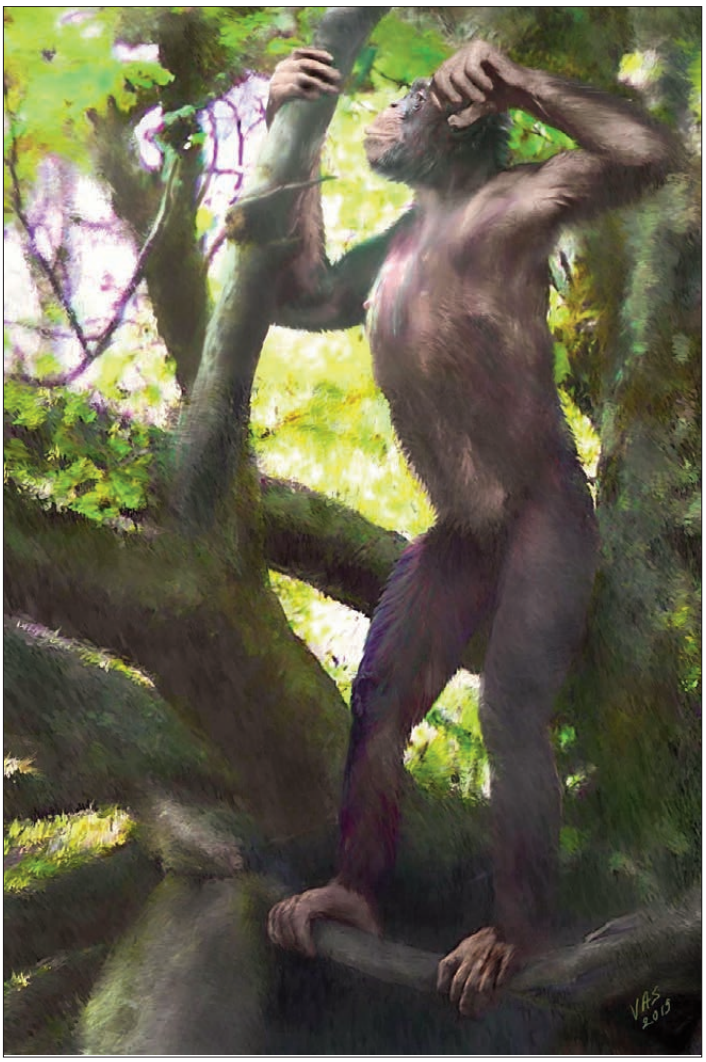

Figure 12 Reconstruction of Danuvius guggenmosi *(copied from Michelson 2019; https://www.smithsonianmag.com/science-nature/new-ancient-ape-species-rewrites-story-bipedalism-180973479/).*

Conclusion

As more fossils continue to be discovered, and as newer dating and genetic techniques are being applied to current fossil collections, researchers continue to unravel and refine the story of human evolution. Genome sequencing of fossils and of modern populations will continue to give useful information. Research into how gene expression alters development is in its early stages.

In another 20 years, the story of human evolution will no doubt be quite different.

(An earlier version of this article was originally published in Footnotes, *OUGS Wessex Branch, July 2020 — Ed.)*

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Rider, Malcolm, and Harrison, Peter 2019 *Hutton's Arse: 3 billion years of extraordinary geology in Scotland's Northern Highlands* (2nd edn). Edinburgh: Dunedin (ISBN 978-1-780-46093-2; x + 226pp; paperback £19.99)

There is no doubt about the huge contribution that James Hutton (1726–1797) made to the science of geology. Hutton, an exemplary product of 'The Enlightenment', was a physician, a merchant, an inventor, a farmer, most probably a bachelor (the authors append a '?' to this aspect of Hutton's character), and a founder member of the Royal Society of Edinburgh. His researches reflect the whole package of an 18th-century 'reflective' Enlightenment philosopher. In Hutton's time, to label oneself as just 'a geologist' would have been atypical. In some ways 'the Enlightenment' could be considered a culmination of the discoveries and revolutions in science of the preceding few centuries. Not so much the questioning of things and the astonishing discoveries about the world and the 'place of humans' in it — new knowledge breaking many long-held moulds of the Classical world — as the cementing with increasing evidence and realisation of, not to say coming to terms with, what that place is. One could argue that the Enlightenment ushered in the 19th and 20th centuries' rush towards knowledge.

James Hutton embodies all these things.

Both authors have decades of experience in research, teaching and public service in Scotland. This book is focused on the Scottish Highlands, but uses Hutton's life and work, and the geology of the Highlands as the springboards for writing about far wider topics.

This beautifully written and produced second edition of the book (originally published in 2005) is another triumph for Dunedin, bringing back into print a book that I think every geologist should own — or at least read.

There are seven long chapters, each complete with its own 'Further Reading' list. These range, as did Hutton's own life and research, through a full gambit of Earth science topics about which geological research in the Scottish Highlands provides relevant evidence. Indeed, the discussions go beyond the Earth, even discussing when the Earth bore some resemblance to modern Mars. There is discovery in the 'The Red Earth: the enigma of the ancient Torridonian'; scientific debate and contention in 'Deep Scar: the Moine Thrust — the story of a bitter scientific controversy'; the beginnings of human evolution in 'The Fish Graves of Achanarras — Devonian fish are our ancestors'; the beginnings of the realisation that the land masses of the Earth are not 'fixed', in 'Volcano — the tertiary volcanic province and the opening of the Atlantic opening'; the ever-present climate 'debate' about and research into impending climate change, in 'The coming Ice Age — past and future climates in the Highlands'; continent- and mountain-building, and their erosion, in 'Left-overs — the Lewisian Gneiss and the creation of continents'; and finally, a more philosophical venturing into pondering our place on Earth, in our Solar System, and in the Universe, in 'Hutton's arse (1795) — just another planet?'

This last 'long' chapter brings us back down to Earth. The authors give us a sober portrait (both in words and in a portrait painting) of Hutton towards the end of his life — only to soar again into the wider world and into space. Hutton himself seems to have come to a sober realisation of how important and insignificant humankind is. He ended his famous, three-volume work on geology with those timely words "…no vestige of a beginning, no prospect of an end…"; in his more private writing he seems simultaneously more whimsical or resigning — whichever way you decide to regard this remarkable man — "My arse, it is evident, is now part of a much greater consequence … than my head … lord pity the arse that's clagged to a head that will hunt stones".

An eighth brief chapter — 'The Future' — is more reflective. It brings the story full-circle, so to speak, in considering the future of the Scottish Highlands, but in the context of Planet Earth at large.

As well as containing lists of further reading, the book includes a detailed index; and is produced on high-gloss paper stock that does justice to its numerous halftone and full-colour illustrations (99 of them, not including the full-page chapter head illustrations). My personal favourites are Figure 7.1 — the aforementioned portrait of Hutton (our only picture of Hutton, even if it is bad art and clearly does not show a 60-year-old man, as Hutton was at the time of its execution); and Figure 5.17 — a drawing of a curiously contemplative-looking extinct giant Irish Elk skeleton. With Hutton gazing to *his* left and Mr. Elk glancing over *his* right shoudler(blade) imagining the two images opposite each other one can only imagine what each would have made of the other.

Any book that mentions both James Hutton's *Theory of the Earth* and Douglas Adams's *Hitchiker's Guide to the Galaxy* in the same sentence has my attention! The price of the book is a mere token for the entertainment, and learning, that Rider and Harrison provide.

— David M. Jones, OUGS Proceedings Editor

The Hebridean island of Raasay

Pauline Kirtley

(Prepared from a talk by Dr Ian Williamson for OUGS Walton Hall Branch 8 February 2020. An earlier version of this article was published in Geo-Log, *OUGS Walton Hall Branch, June 2020, 4–23 — Ed.)*

Dr Ian Williamson has long held a special interest in the geology and landscapes of the Inner Hebrides, and in particular, in their spectacular Palaeocene volcanic rocks; his PhD and continuing research interests focus on various aspects of the Skye and Mull lava fields. Keen to share his expertise in this field, he has led several successful OUGS field trips to Skye, Mull and Ardnamurchan and has presented talks to several regional and professional groups; he was also a speaker at the 2017 OUGS Symposium in Edinburgh.

Ian's talk was about the island of Raasay, which lies a short distance east of the better-known Isle of Skye. Despite its relatively small size, it is a microcosm of many of the geological formations seen throughout the Hebrides. Outlining his talk, Ian told us that he would cover aspects of the island's geology and attempt to show how the landscapes formed by the underlying geological processes have shaped the island's peoples and history.

Geology

Geologically speaking, Raasay lies within the so-called Hebridean Terrane, one of the four mega-structural elements that make up Scotland (Fig. 1).

Using the published BGS geological map Ian briefly introduced the range of geological periods and formations of the island. These range from the Archaen Lewisian Gneiss Complex in the north, through the Neoproterozoic Torridonian Supergroup in the north-central parts of the island, to the Mesozoic and Palaeogene formations of the in the south (Fig. 2).

The geology, landscapes and 'cultural' associations of these areas were then illustrated in turn.

Northern Raasay — Archaen

The Lewisian Gneiss Complex is a very old assemblage of highly metamorphosed rocks, and is interpreted as having been progressively accreted from disparate continental crustal blocks of Archaen continental crust and juvenile Proterozoic arcs.

The oldest protoliths have been dated at *c.* 3000Ma. This 'assemblage' has been referred to as the Rona Terrane, a subset of the Hebridean Terrane, after the island of that name directly north of Raasay. The rocks are predominantly high-grade, much deformed granitic gneisses intruded by mafic amphibolite sheets (? Scourie Dykes) and some migmatites. Figure 3 *(overleaf)* is a roadside cutting showing an example of these banded pink feldspathic and mafic gneisses.

Although these rocks form a mostly barren and treeless, hilly and glacially sculpted terrain with little soil and rugged coastlines, quite a sizeable human population lived within this landscape from time to time. However, life was never easy and in this northern part of the island there were no roads, so the only access

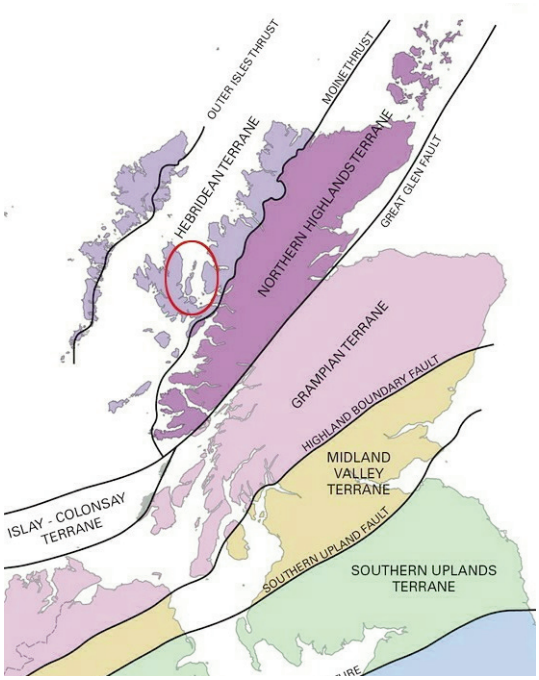
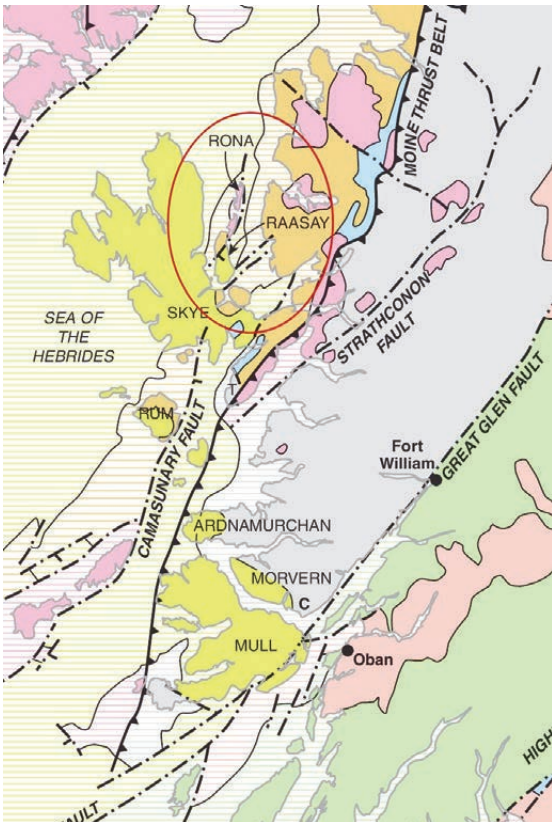


Figure 1 Raasay: location and geological setting. Key to Map 2: yellow = Palaeogene and Mesozoic; light pink = Silurian-Devonian; blue = Cambro-Ordovician; orange = Torridonian; blue-grey = Moine Supergroup; green = Dalradian Supergroup; dark pink = Lewisian Gneiss Complex.



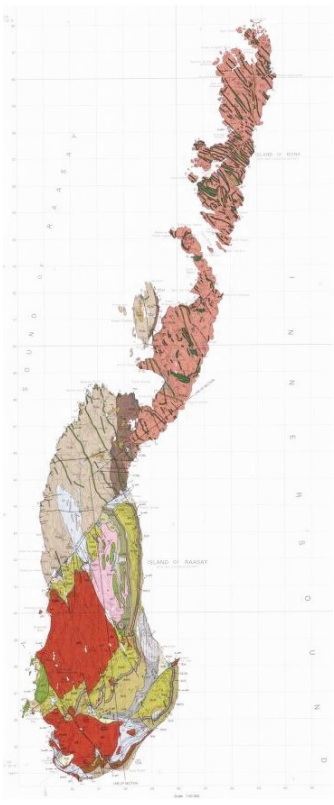


Figure 2 Outline geology of Raasay.

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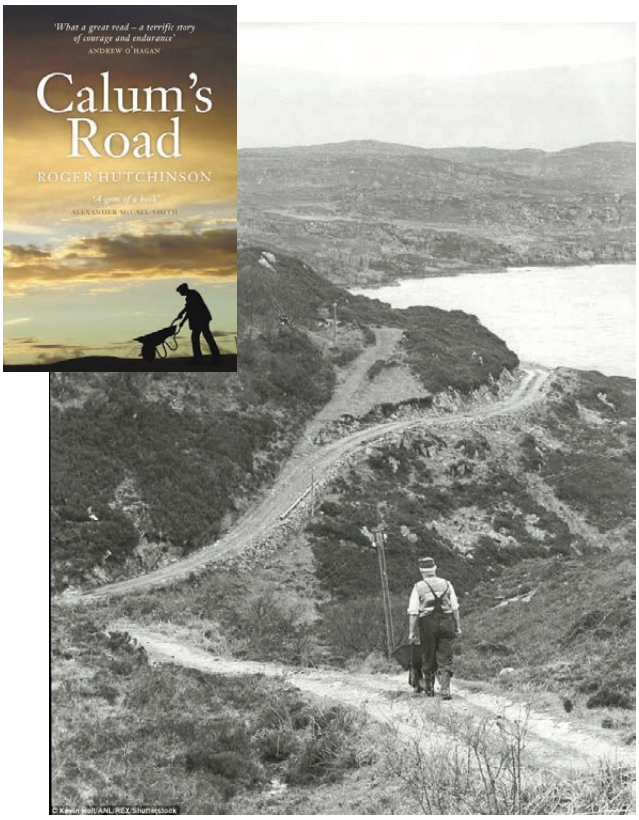
Figure 3 Tairbeart road-cut exposures. Gneisses were reworked during the Laxfordian event and the fabrics developed reflect this overprinting. Raasay's TTG 'granitic' gneisses are predominantly grey to pink with an average composition of granodiorite. Deformation caused boudinage in a suite of mafic sheets with boudins separated in places by granite pegmatite.

was on foot or by boat. The car park above Brochel was where the original surfaced road finished. Hence, any crofters living north beyond this point had difficulty keeping in contact with the southern part of the island.

A local story, which has been well documented, tells of one man, Calum MacLeod who, frustrated by politics and bureaucracy, took it upon himself to build the road alone. Over a period of 12 years he laboured with pick, shovel and wheelbarrow until it was completed and it is now known as 'Calum's Road' (Fig. 4).

Figure 4 Between the mid-1960s and the late 1970s, one crofter, Calum MacLeod, taking matters into his own hands, almost single-handedly built what is now known as 'Calum's Road' across the Lewisian landscape of north Raasay.


'What a great read – a terrific story of courage and endurance'
ANDREW O'HAGAN
Calum's Road
ROGER HUTCHINSON
'A gem of a book'
ALEXANDER McCALL SMITH

Northern-Central Raasay — Neoproterozoic

Overlying the Lewisian Gneiss Complex is the Neoproterozoic Torridonian Supergroup, which consists of a suite of predominantly clastic sedimentary rocks deposited on the eastern margins of the former supercontinent of Laurentia at *c.* 1200Ma to 950Ma.

These sediments infilled valleys and channels within an ancient Lewisian landscape; one slide illustrated the unconformity between the two elements. This was a continental style depositional environment, possibly a rift valley, with alluvial fans, playa-style lakes, and braided rivers. These sedimentary rocks, mudstones to coarse conglomerates and breccias, are tough but not regionally metamorphosed. Two formations are present. A lower Diabaig Formation, composed of interbedded mudstone, siltstone and fine-grained sandstone; early prokaryote and eucaryote microfossils have been found in some. Above these lies the Applecross Formation, an arenaceous unit present across much of the north-western highlands. Many beds show evidence for soft sedimentary deformation, such as homogenisation, slumping and overturned cross-bedding, possibly resulting from liquefaction of water-saturated sands (Fig. 5, *opposite*).

Ian drew a geology-landscape connection to the 1745–46 Jacobite rebellion and Raasay. Within one of the many stream sections exposing the Torridonian on the western side of the island, there was a hut within which Bonnie Prince Charlie, who spent two days on Raasay, reputedly stayed. The Clan Chief at the time wanted to fight for the Prince, but, being savvy enough to know he couldn't win, bequeathed his estate on Raasay to his son, who stayed loyal to the Crown. Initially this taking of sides had little effect, but this all changed following the rebellion, when it was discovered that Charles had been harboured on the island. What followed was a series of particularly brutal reprisal attacks by Government troops.

Southern Raasay — Mesozoic

In the southern part of the island there is a thick succession of Mesozoic strata, ranging in age from Triassic through to Cretaceous.

Figure 6 *(opposite)* shows a beautiful photograph of the coastal scenery north of the locality of Rubha na 'Leac, which nicely illustrates the stratigraphical sequence. This photograph also shows the summit of Paleogene lava capping Dun Caan, Raasay's highest point, faulting and some Quaternary landslips.

Triassic rocks are represented by the strikingly red rocks of the Stornoway Formation (New Red Sandstone Group). They consist of interbedded sheets of conglomerates, breccias and sandstones separated by thin interbeds of siltstone, caliche and palaeosol horizons. Four fining-upwards units displaying large-scale trough cross-stratification have been recognised. The conglomerates and breccias are polymict and carry clasts of Lewisian gneiss, quartzite, sandstone, basalt, and Cambrian and Ordovician limestone-dolostone.

Figure 7 *(oppoiste)* is a photograph of Rubha na 'Leac. On it Ian pointed out the lower sequence, which is dominated by conglomerate and intruded by some Palaeocene dykes.

The Stornaway Formation has all the features of a sequence deposited in a predominantly arid desert-like environment, most likely in an alluvial fan setting subject to periodic flash-flooding and debris-flow events.

Figure 5 Deformation was most likely triggered by flood-induced turbulence and water release following rapid deposition, seismically induced liquefaction or upwelling groundwaters.

Figure 7 Rubha' an Leac, south-east Raasay, Stornoway Formation: conglomerates, breccias and sandstones interbedded with lenses of siltstone and caliche (calcrete palaeosol) horizons, likely deposited in an alluvial fan system involving debris flow, stream flood, braided stream, playa lakes and pedogenesis.

Lower and Middle Jurassic

This sequence is composed of fluvio-deltaic, estuarine and also fully marine strata. The lowermost unit of the Lower Jurassic — the Breakish Formation — for example, consists of alternating beds of micritic limestone and silty mudstone, many carrying bivalve-dominated fauna, which includes gryphaea and ammonites. It is interpreted as a nearshore marine deposit (Fig. 8, *overleaf*).

Moving on to the Middle Jurassic, Ian explained that several thick sandstone bodies, alternating with thick argillaceous units, form much of the cliff line on the eastern side of the island. The sandstones, for example the Bearreraig Sandstone Formation, are composite units with complex internal sedimentary facies architectures (Fig. 9, *overleaf*).

The Jurassic-dominated landscapes of southern Raasay are gentler than those of the northern (Lewisian and Torridonian) parts. Soils, including those developed on later glacial deposits, are varied and the land is more fertile and better for farming, and for the development of organised townships. This north-south

Figure 6 View looking towards Dun Caan from Rubha na 'Leac.

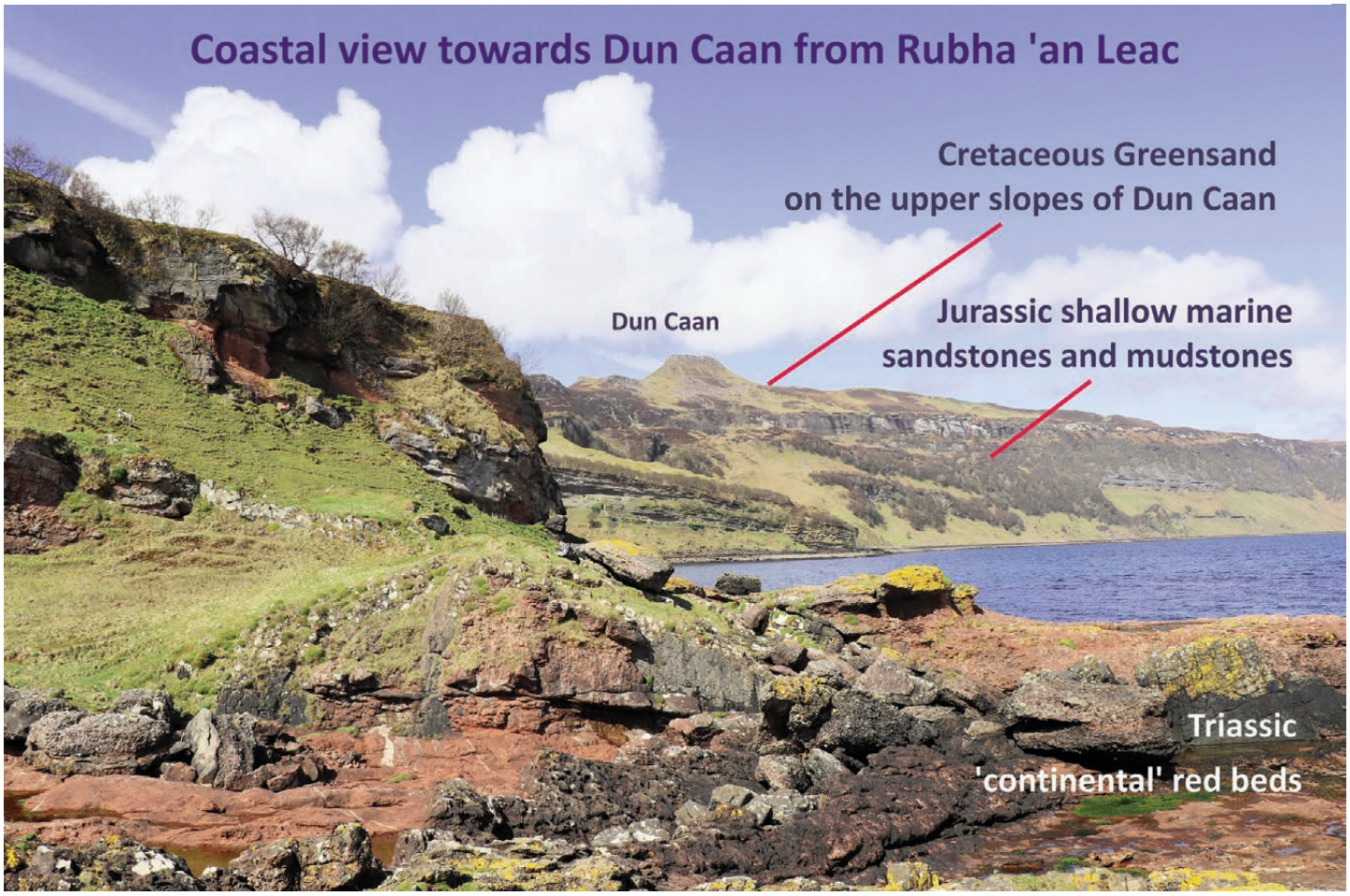


Figure 8 Lower Jurassic Breakish Formation: interbedded limestone and silty mudstones with a bivalve-dominated fauna, including Gryphaea, Modiolus, Cardinia and Liostrea. Ammonites are also present.

Figure 9 Jurassic sedimentation: geology and landscape, Hallaig Bay to Screapadal, south-east Raasay. Alternating marine sandstone- and mudstone-dominated formations followed by sandstones and shales deposited under lagoonal, deltaic and fluvial environments (thickness 300m+).

contrast is illustrated by Figures 10 and 11. Figure 10 shows a view from Raasay House looking across to Skye in the 1770s and some farmland. In contrast to the north of the island, the south had relatively productive soils supporting a sizeable population before the 1840s, as shown in Figure 11.

One particular feature of the Jurassic rocks of south Raasay played a pivotal role in the island's economics — the Raasay Ironstone. This rock was laid-down under shallow marine conditions, and though fairly thin, is regional in its extent and may be traced throughout most of the Inner Hebrides. Lithologically this formation is very tough and hard, thinly bedded, chamositic to

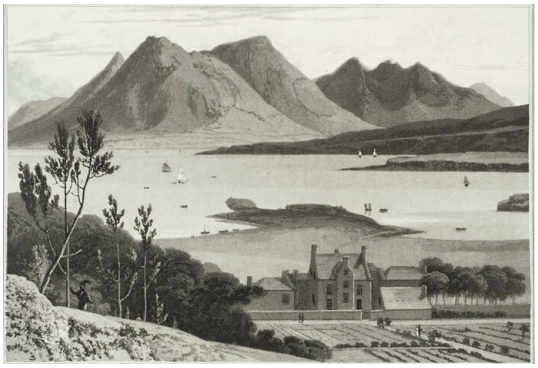


Figure 10 (below left) Raasay House looking towards Skye in the late 1700s. The soils developed on the 'Jurassic' lands of southern Raasay were much more productive than those of the stony north.

Figure 11 (a and b, above) Present day farming on Raasay; (c and d, below) crofting in the early 20th Century.

sideritic and ooidal. Fossils include ammonites and belemnites. It was mined during the early 20th century. The remains of some of the infrastructure from these industrial processes dot Raasay's landscape today (Fig. 12). Ian showed photographs of the entrance to the mine and also where the ironstone was crushed and processed. Mined north-east of the village of Inverarish, the raw ore was taken by a railway to East Suisnish, where it was crushed and processed before being loaded onto ships for transportation.

The ironstone was worked and exported for steel production, mainly during the period of the First World War. In the UK, most men were at war or part of the war effort at this time, so German prisoners of war were used as labour. Using prisoners of war in this way was a breach of the Hague Convention; the formal records of this use of the prisoners were 'conveniently lost' after the war. Laurence and Pamela Draper have written a comprehensive, illustrated account of the ironstone industry on Raasay: *The Raasay Iron Mine 1912–1942 (Where enemies became friends*) (ISBN 978-0-9514870-0-6).

Cretaceous

A small outcrop of Upper Cretaceous strata is present on the high eastern slopes of Dun Caan. This is the Morvern Greensand Formation, typically a glauconitic, medium-grained sandstone.

Cenozoic

Palaeogene

Ian is an acknowledged expert on the Palaeogene, the period of mid-Palaeocene volcanism roughly between 60 and 58 million years ago, and which is related to sea-floor spreading initiating the opening of the North Atlantic Ocean and mantle plume activity. At this time several large volcanoes developed along the western seaboard of Scotland. Today, the hearts of these volcanoes are represented by the suites of plutonic rocks that characterise the mountainous 'central complex' areas of Skye, Rum, Ardnamurchan and Arran.

On Raasay, igneous activity exists only as a small outlier of the Skye Lava Field (one of three extensive lava fields in the Hebrides) and some sills and dykes. The outcrop of lavas on Raasay is a comparatively small , and occupies some of the high ground on and around the island's highest point — Dun Caan. Ian compared their eruptive style and facies with the fissure-fed lava fields of Iceland.

Ian pointed out the prominent dip slopes in the Jurassic beds, and the crags of the Raasay Sill (riebeckite microgranite) (Fig. 13, *overleaf*). In the background is north Skye. Ian drew our attention to the prominent stratification and terracing of the lava field on Skye; in the distance was the famous Storr.

Ian next pointed out the main geological features in a photograph of Dun Caan (Fig. 14, *overleaf*). To the right is a dolerite sill intruding Jurassic sandstones; the outcrop of the Cretaceous mentioned previously is on the left-hand side, and lavas cap the hill itself. The lava on the top shows flow-banding typical of pahoehoe basalts, but Ian pointed out that with his experience of mapping the Skye and Mull lavas, there also seems to be a correlation with those of more intermediate composition (hawaiites rather than basalts) (Fig. 15, *overleaf*).

Dun Caan has another interesting historical connection on the island. The famous lexicographer Samuel Johnson and his sidekick James Boswell visited the Hebrides. They stayed at Raasay

Figure 12 (a and b, above) Mine entrance and former opencast workings; (c and d, below) the old pier at Suisnish and the former ore hopper and kilns.

Figure 13 The view towards Skye from near the old pier at East Suisnish, south Raasay.

House and Boswell walked to the top of Dun Caan where he reputedly danced a highland jig.

The medieval castle of Brochel in north-east Raasay was a clan stronghold, and would have been well protected by the local terrain. Its ruin sits on an outcrop of coarse breccia, the geological origins of which are still debated (Fig. 16). Until recently this formation has been explained as a Palaeogene vent 'agglomerate', a collapsed volcanic pipe or small volcanic necks infilled with volcaniclastic material. However, Ian pointed out that looking more closely at the lithology, structure and internal features here and in other outcrops on the hillslopes to the north, it is possible to come up with an alternative and very different explanation.

Typical exposures show no igneous material present, only large angular clasts of Torridonian rocks (possibly Diabaig Formation) and crude, lobe-style bedding and imbrication. It appears to sit within a palaeovalley that had been eroded into the local Lewisian and Torridonian. Ian thinks that it could be better interpreted perhaps as a series of conglomerate-debris-flow sedimentary units of Triassic age, broadly equivalent to the Stornoway Formation conglomerates.

Quaternary–Recent

Ian went on to briefly describe the island's Quaternary–Recent geology, and the evidence for glacial and post-glacial processes, such as the glacially-striated Lewisian, scattered tills and hummocky deposits, rock platforms, raised beach deposits, cave systems and landslips.

In a panoramic view slide of the wonderful panorama of the scenery visible from Dun Caan's summit Ian pointed out the back scars of impressive landslips (Fig. 17, *opposite*). Another slide showed a close up of the rock fissures, which are deep and precarious.

Ian also described the historical development of crofting in the landscape. On the slopes below Dun Caan there are the ruins and

Figure 14 Dun Caan seen from the west.

Figure 15 Contorted flow-banding in lava on the summit crags of Dun Caan.

field patterns of the abandoned 'clearance' village of Hallaig. The Highland Clearances implemented waves of cruel evictions of tenants from their lands at the behest of unscrupulous landlords more concerned with generating income through sheep farming and shooting estates. On Raasay, a large proportion of the population was forced to relocate to the already impoverished, soil-poor and bleak north of the island — the only place on the island where they were allowed to stay and possibly eek out a living.

No talk on the Hebrides would be complete without alluding to landscape-inspired folktales and myths, and Raasay is no different. There was said to be a Kelpie, a malevolent water spirit of Scottish folklore, inhabiting one of the lochs near Dun Caan, and witches supposedly held satanic rights on the flat summit of the hill (Fig. 18, *opposite*).

There are also tales of fishermen having trouble travelling between Raasay and Skye, and of their boats being boarded by hundreds of black cats.

Conclusion

In conclusion, Ian said that Raasay is, in many ways, a very special island. Its appeal to us lies in its very diverse geology, easy access and that incredible, unique feeling of really being on an island, and one that is so much more tranquil than its more

Figure 16 The Brochel Breccias: an enigmatic suite of rocks shown on current BGS maps as Palaeogene Volcaniclastic Breccia — volcanic pipes filled by the downward collapse of cover formations during explosive fumarolic activity. But is there an alternative interpretation? (see text)

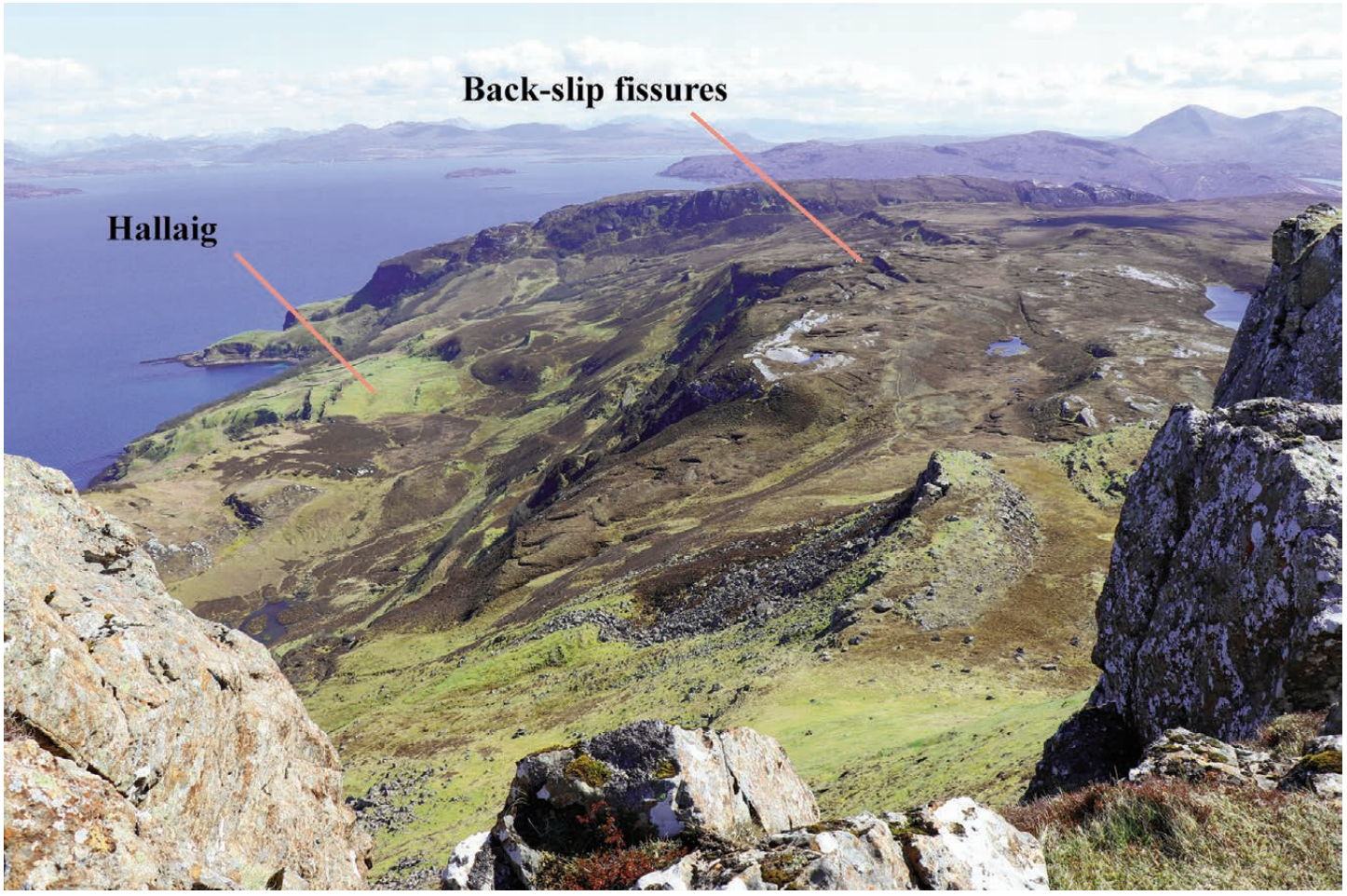


Figure 17 View looking south from the summit of Dun Caan. The most significant, and certainly the most spectacular, post-glacial process has been the development of an extensive rotational landslip terrain.

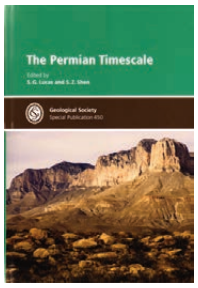
'touristic' neighbour, Skye. He said it is ideal for fieldtrips, as it is possible to cover a huge amount of geology even in one day, and highly recommends that if you are ever staying on Skye, do take the ferry across to Raasay. You'll not regret it.

Acknowledgement

I am very grateful to Dr Williamson for his significant input during the writing and completion of this article. Without the time Ian gave to this, and the inclusion of his photographs, it would not have been possible to present such a comprehensive report of his talk.

Figure 18 Landscape folklore: the Devil, witches and black cats. The flat-topped summit of Dun Caan (Palaeocene lava) was sometimes referred to as 'Satan's Table', and reputably believed to be the haunt of dancing witches on May Day Eve and at Hallowe'en.

Book review



Lucas, S.G., and Shen, S.Z. (eds) 2018 *The Permian Timescale*. London: Geological Society Special Publication 450 (ISBN 978-1-78620-282-6; 458pp; hardback £120)

This book is one of the Special Publications put out by the Geological Society, consisting of a series of papers of up-to-date research on a particular subject: in this case The Permian Timescale. Both the Introduction and the paper on the history, status and prospectus of the Permian chronostratgraphc scale highlight the work of the Subcommission on Permian Stratigraphy (SPS), which started in the early 1970s. The SPS is continuing the work that has been ongoing since the naming of the Permian by Sir Roderick Murchison in the mid-1800s. So far the Permian timescale consists of nine stages, split into three series. The SPS recognises the boundaries of the Permian and the base of six of the stages as defined by global stratotype sections and points (GSSP) based on the evolution of conodonts. Work is still in progress to establish GSSP for the remaining stages. Although these are also expected to be based on conodont evolution, the introduction also draws our attention to the other work being done to correlate sections around the globe, as not all Permian strata contain conodonts.

The papers in the book cover the following subjects, which are being researched in order to correlate the Permian strata around the world:

- radioisotopic geochronology
- geomagnetic polarity
- strontium isotopes
- donodonts
- radiolarians
- rugose coral
- ammonoids
- small foraminifers
- fusulines
- brachiopods
- palynography
- macroflora
- conchostracan
- tetrapods

While the Introduction and the first two papers in this book set out the history of defining the Permian Timescale and how the stages have been, and are still being, determined are interesting and readable for the novice geologist, the rest of the book is not what you might call ‘light reading’. This is definitely not a ‘cover-to-cover’ read. There is a lot of technical language in these papers, which are aimed at the serious researcher of the Permian Timescale or the more experienced geologist with an interest in all things Permian. There are no equations, or mathematical or /chemical formulae to wade through, and although there are charts, graphs, maps and photographs throughout the book, they are a little on the sparse side. There is, however, a lot of text mostly presented as lists.

The majority of the papers are about research on various fossil types, complete with Latin nomenclature, which is necessary but makes for difficult reading unless this happens to be your field of interest. However, if you have enough knowledge to pick your way around the Latin names and the technical detail of the organisms being studied there is some quite interesting information to be garnered about Permian strata in various places around the globe. Oddly I found the papers on radioisotopic geochronology, geomagnetic polarity and strontium isotopes to be easier reading than most of the biological-based papers, apart from the papers about tetrapods. This probably says more about my knowledge of the Latin names of organisms than it does about the book!

What the papers in this book highlight is the need for more research to define the missing GSSPs and to correlate the Permian stratigraphy across the globe, as it seems that there are still a good many gaps to be filled. This book could be a good jumping off point for anyone looking for a research project.

— Linda Morley, BSc (Hons) Natural Sciences with Earth Sciences, MSc in Earth Science

The Carboniferous basal unconformity in the Craven Inliers: exposures at Nappa Scars, Crummack Dale, N. Yorkshire

Duncan Woodcock

Regional background

Marine sediments were deposited over much of north-west England during much of the Ordovician and Silurian periods. These sediments were deformed in the early- to mid-Devonian during the Acadian Orogeny, resulting in the development of a cleavage, together with uplift and subsequent erosion. This transpressional phase was followed by north–south extension in the late Devonian, when areas underlain by granites behaved as rigid and buoyant blocks. Sedimentation during the early Carboniferous marine transgression was strongly controlled by the resulting 'block and basin' topography, with thick sequences of sediments deposited within the basins while thinner sequences of shallow-water platform carbonates were progressively deposited on the blocks. In both cases, deposition occurred on an eroded pre-Carboniferous surface, giving rise to the regional unconformity at the base of the Carboniferous in north-west England (Waters and Davies 2006).

The Craven Inliers

The Carboniferous basal unconformity is particularly well displayed at several locations around the edge of the Craven Inliers in north Yorkshire (Fig. 1). These inliers lie on the southern edge of the Askrigg Block, immediately to the north of the North Craven Fault (Aitkenhead *et al.* 2002). They comprise Silurian, Ordovician (and possibly Precambrian) cleaved siltstones and sandstones that are unconformably overlain by subhorizontally-bedded Carboniferous limestones.

Figure 1 shows a number of locations where the unconformity is particularly well exposed. At most locations, limestone lies directly on the older rocks, or is separated from them by 1–2m of conglomerate. Thus, on the north-west side of Chapel le Dale, cleaved siltstones are unconformably overlain by *c.* 0.5m of pebbly, clast-supported conglomerate, in turn overlain by *c.* 1m of coarse, angular matrix-supported conglomerate (Fig. 2), and then by *c.* 0.5m of limestone containing lenses of siliciclastic granules that grade upwards into 'normal' (clast-free) limestone. At Thornton Force, similar lenses of siliciclastic granules lie *c.* 1m above the unconformity (Fig. 3, *overleaf*). In contrast, at Nappa Scars in Crummack Dale the conglomerate extends for *c.* 12m above the unconformity.

Figure 2 Coarse angular matrix-supported breccia, about 1 m above the unconformity on the NW side of Chapel le Dale, Ingleton (SD 7115 7548). Height of exposure c. *0.3m.*

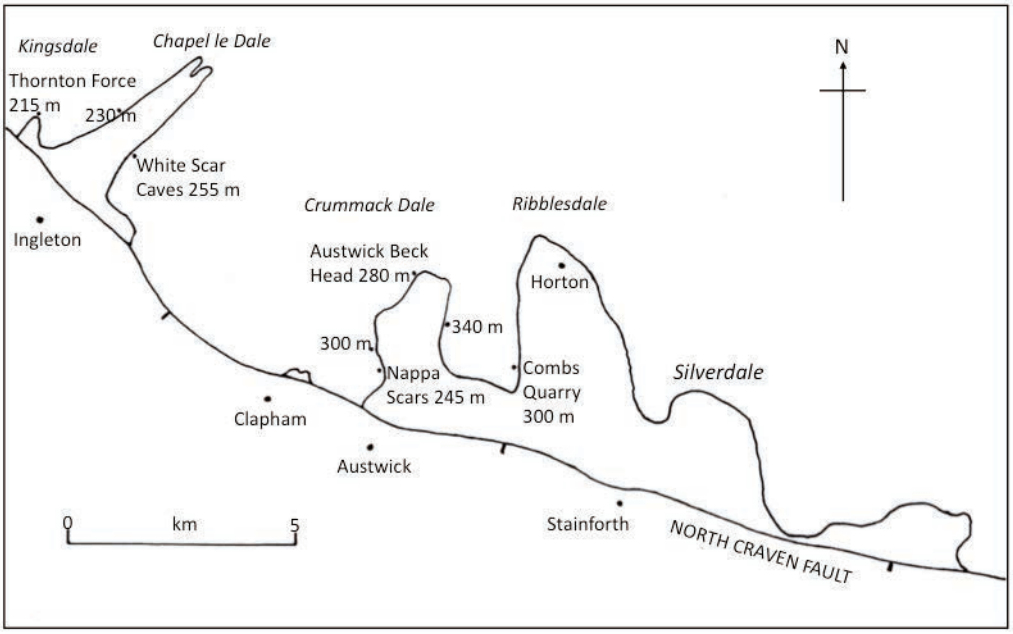


Figure 1 The Craven Inliers are bounded by the North Craven Fault to the south-west and by the unconformity between the lower Palaeozoic rocks and the overlying Carboniferous Limestone. Locations identified on the unconformity are places where the unconformity is particularly well exposed. The altitudes (in m above MSL) recorded at each location indicate considerable topography on the unconformity surface.

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Figure 3 Lenses of siliciclastic grains in limestone, west side of Thornton Force, c. *1m above the unconformity (SD 695 753) (height of exposure* c. *0.5m).*

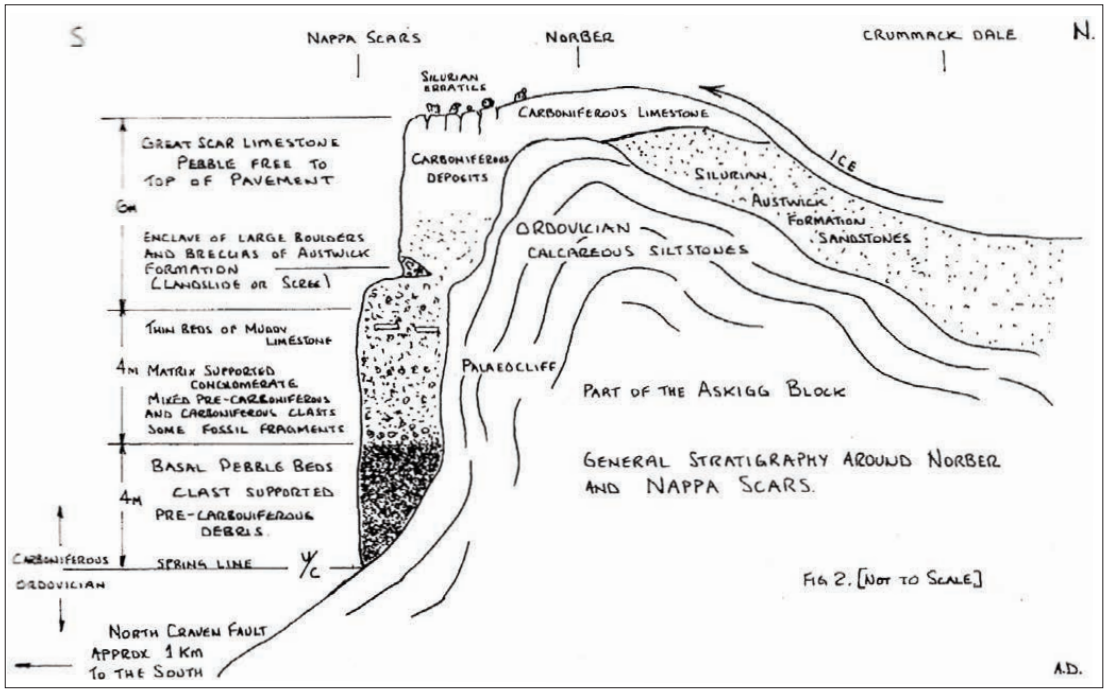
The exposures at Nappa Scars

The exposures at Nappa Scars are described briefly in some field guides (e.g. Johnson 1994). One of the best existing descriptions is a summary diagram (Fig. 4) produced by OUGS NW member Alan Diggles (Diggles 2000), which shows the conglomerate onlapping onto a palaeocliff in Ordovician siltstones. The purpose of the rest of this note is to provide a detailed description of the exposures at Nappa Scars, supported by a map of selected locations (Fig. 5), a composite graphic log (Fig. 6, *opposite*) and a set of photographs (Figs 7–18), in which I attempt to illustrate the various features of this outstanding location.

The exposures at Nappa Scars can be accessed most easily by taking the footpath west-north-west from Crummack Lane at SD 7722 6965. Below the footpath, at 7699 6975, a low cliff starts adjacent to a hawthorn tree. At Location 1 (Fig. 5) there are exposures of pebbly clast-supported conglomerate — these are the Basal Pebble Beds on Figure 4. They comprise rounded to subrounded, often ellipsoidal pebbles of sandstone and siltstone, typically 3–10m long (Fig. 7, *opposite*).

The cliff can be followed for *c.* 30m west to Location 2, where the Basal Pebble Beds overlie cleaved siltstones above an irregular erosive unconformity surface (Fig. 8, *page 70*). The siltstones were deposited in the late Ordovician (Caradoc-Ashgill age). The cleavage, which dips *c.* 70° south-west, developed during the Acadian Orogeny. The Basal Pebble Beds show crude, subhorizontal, slightly undulating bedding (Fig. 9, *page 70*) that is defined by variation in clast size. Locally, the clast-supported conglomerate grades into lenses in which small matrix-supported clasts weather proud of the surface (Fig. 10, *page 70*). About 20m farther west and 1–2m vertically below, there is a further exposure of the unconformity (Location 3) within a recess below overhanging beds of conglomerate.

Figure 4 Summary cross-section of the stratigraphy around Norber and Nappa Scars, Crummack Dale, showing c. *14m of conglomerate above the unconformity onlapping a palaeocliff of Ordovician siltstones (from Diggles 2000, with permission).*



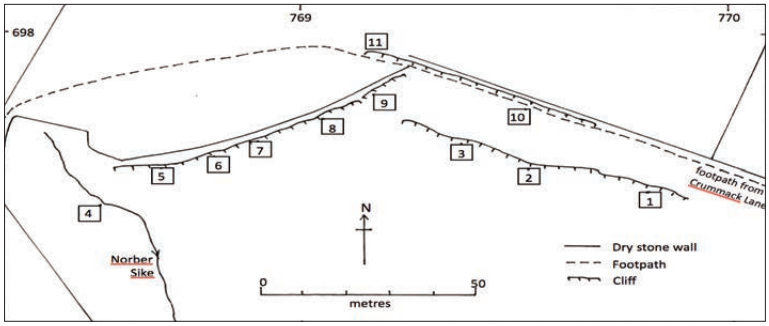


Figure 5 Sketch map of the exposures at Nappa Scars, Crummack Dale, showing the locations referred to in the text.

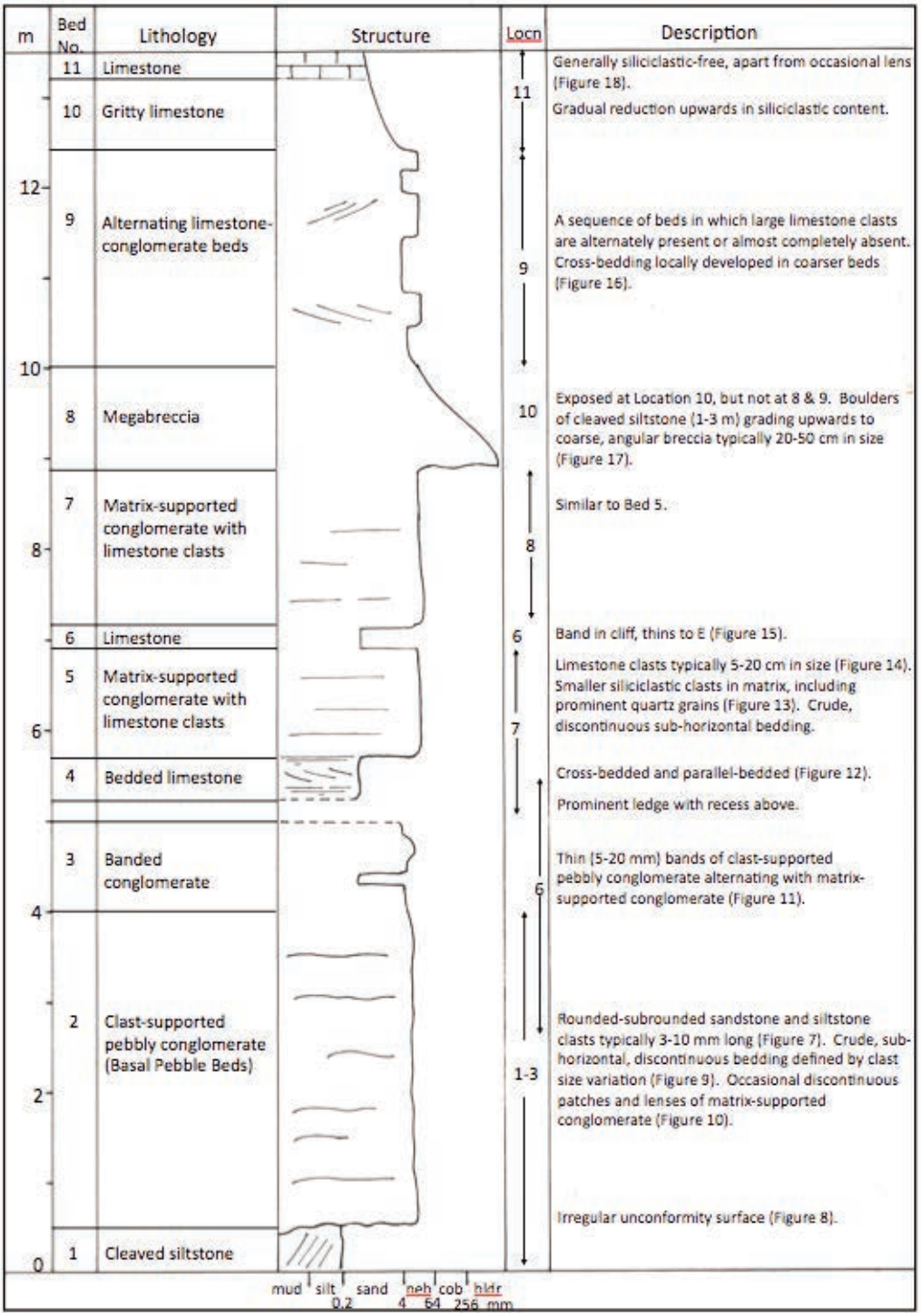


Figure 6 Composite graphic log through the conglomerates above the unconformity at Nappa Scars, Crummack Dale. The LHS column (headed 'm') indicates height in metres above a datum just below the unconformity at Location 3. The numbers in the 'Locn' column refer to the numbered locations on Figure 5.

Figure 7 Clast-supported pebbly conglomerate of the Basal Pebble Beds between Locations 2 and 3 at c. *1m on the composite log. The pebbles are typically 3–10mm long and ellipsoidal in shape.*

Figure 8 Ordovician siltstones with a cleavage dipping at 70–80° south-west are unconformably overlain by the Basal Pebble Beds at Location 2. (height of exposure c. *2m).*

At this point traverse west-south-west and slightly downhill to intercept the small stream known as Norber Sike. There is an exposure of cleaved siltstones in the stream bed at Location 4, from where water generally enters the stream bed during dry periods. Above this location, much of the stream bed is covered by boulders, apart from three prominent horizontal benches, probably of conglomerate, that are covered with vegetation, suggesting flow of water higher up in the stream bed during wetter conditions. The unconformity at Location 4 lies some 10m vertically below the unconformities at Locations 2 and 3, indicating that the surface of the unconformity has significant topography locally as well as regionally (*see* Fig. 1).

Figure 9 Exposure of the Basal Pebble Beds unconformably overlying cleaved siltstones at Location 3 (hiking pole c. *1.4m long). The pebbly conglomerate shows a crude, subhorizontal, slightly undulating bedding.*

Figure 10 Prominent elongate lens of matrix-supported conglomerate within Basal Pebble Beds between Locations 2 and 3 at c. *2m on the composite log (field of view 110 ¥ 160mm).*

Figure 11 Contact between clast-supported Basal Pebble Beds (below) and the 'banded conglomerate' bed (above), which comprises matrix-supported conglomerate with thin bands of clast-supported conglomerate. Location 6, c. *4.5m on the composite log (largest pebbles* c. *10mm long).*

From Location 4, traverse *c.* 20m north-east to further exposures of the Basal Pebble Beds at Location 5. These beds extend east for another 20m or so, where there are two wooden fence posts, one bearing a ceramic insulator. Here, at Location 6, the clast-supported pebbly conglomerate is overlain by a layer *c.* 0.5m high within which bands (5–20mm thick) of clast-supported conglomerate alternate with a matrix-supported conglomerate (Fig. 11, *previous page*). This layer is terminated upwards by a prominent ledge with a recess above.

The ledge and recess mark a distinct change in the nature of the conglomerate. In contrast to the underlying Basal Pebble Beds the overlying conglomerates are much more variable, both laterally and vertically. In general, they are matrix-supported and contain large limestone clasts and smaller siliciclastic clasts, although there are layers that are substantially free of clasts. These may be studied most easily at Locations 7 to 9. The detail of the sequence at these locations is summarised on the composite log (Beds 4–7 and 9) and illustrated by Figures 12 to 16.

Figure 12 Cross-bedded and parallel-bedded layers of the 'bedded, clast-free limestone' at Location 7, overlain by c. *0.8m of matrix-supported conglomerate with limestone clasts.*

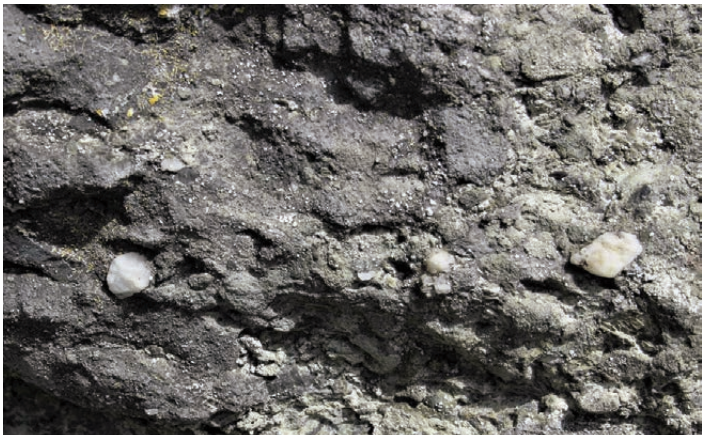


Figure 13 Close-up view of the matrix between the limestone clasts in Figure 12. The conspicuous clasts of milky quartz are c. *10mm in size, while much of the matrix is much finer grained.*

Figure 16 (right) A sequence of beds c. *3m high, in which large limestone clasts are alternately present or almost completely absent — Location 9, at 9.5–12.5m on composite log.*

Figure 14 Matrix-supported conglomerate with large (30–100mm) limestone clasts — Location 7, at 6.6m on composite log (width of hiking pole at lower-right 20mm).

Figure 15 Bed of clast-free limestone c. *200mm thick in the cliff face above Location 6 at 7m on composite log. This bed gradually pinches out eastwards over 2–3m.*

Just beyond Location 9 there is a gap in the line of the cliff and a change in orientation. Here, the upper cliff runs just south of east with a footpath along its base (*see* Fig. 5). At Location 10 the footpath runs over a slightly convex surface of siltstone, *c.* 3m long. The adjacent cliff comprises coarse, angular breccia with boulders of cleaved siltstone up to 1m in size (Fig. 17). This coarse 'megabreccia' is not present at the corresponding stratigraphic height at Locations 8 and 9, suggesting that it is a localised feature.

At Location 11 small granules of siliciclastic material are supported within a limestone matrix. There is a gradual reduction in the siliciclastic content upwards into 'normal', limestone, although the occasional lens rich in siliciclastics can be observed. Such lenses tend to weather to a gritty surface (Fig. 18) and act as a useful indicator of proximity to the unconformity when approaching it from above at other locations.

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Figure 17 'Megabreccia' in recess at Location 10, at 9–10m on composite log. The slightly convex surface in part sunlight at the bottom of the picture is part of the top of a large siltstone boulder c. *3m long. The angular boulder of cleaved siltstone above is* c. *1m long.*

Figure 18 A lens containing a 'rash' of small (2–3mm) siliciclastic grains — Location 11, at c. *13m on the composite log. This patch is atypical; at this location much of the limestone is substantially free of siliciclastic material.*

Some Geological Sites of Special Scientific Interest in Swindon and north Wiltshire

Dick Millard

Part 1 Swindon's SSSIs: the Old Town Railway Cutting and Great Quarry

History

Swindon's Old Town hill is a late Jurassic to early Cretaceous outlier of Portlandian and Purbeck rocks (Fig. 1). The area has been quarried since Roman times; remains of some Roman buildings discovered here are of stone from such quarrying. There was no freestone, but much rubble. Some of the fissile Purbeck beds were used for flooring. The 17th century antiquarian John Aubrey commented:

> *At Swindon is a quarrie of stones, excellent for paveing halls, staire-cases, &c; it being pretty white and smooth, and of such a texture as not to be moist or wett in damp weather. It is used at London in Montagu-house, and in Barkeley-house &c. This stone is not inferior to Purbac grubbes, but whiter. It takes a little polish, and is a dry stone. It was discovered but about 1640, yet it lies not above four or five foot deep. It is near the towne, and not above [ten] miles from the river of Thames at Lechlade.(Aubrey 1847)*

This flooring was used in the re-building after the Great fire of London. Quarrying accelerated with the arrival of canals in 1810 and again later when the Great Western Railway came through in 1841. By the second half of the 19th century the quarry was worked out. It is now public gardens, laid out in two stages in 1894 and 1902.

Just before this, in 1881, the Swindon and Marlborough Railway was opened. After failing to tunnel through the Old Town hill, the railway company decided on a route around the western side of the hill. This involved a cutting, in the sides of which conveniently show strata directly below those displayed in the quarry faces (Fig, 2).

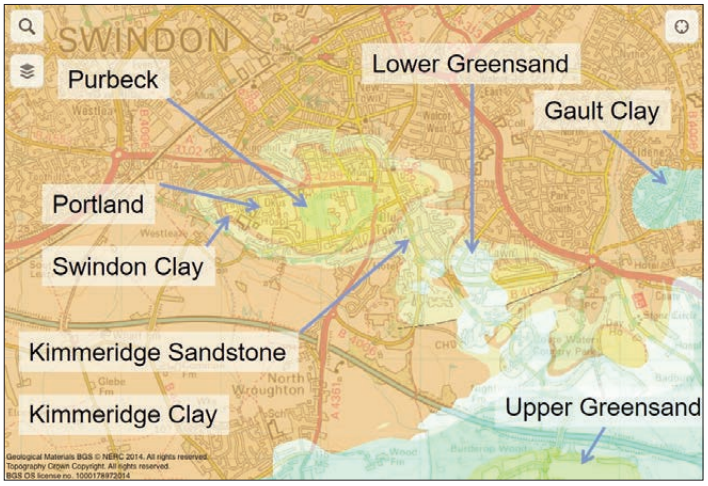

Figure 1 Geology of Swindon Hill outlier (Contains British Geological Survey materials (C) UKRI [2020] Source: https://www.bgs.ac.uk/technologies/apps/igeology-app/ — reproduced courtesy of BGS).

The exposures were first studied while and just after the quarry was in operation in the mid-19th century, and when the railway was constructed in 1879. The descriptive geology was summarised by Sylvester Bradley (1940), amended by Arkell (1948) and interpreted in terms of sequence stratigraphy (and correlated across the Wessex Basin) by Coe (1996).

Outline geology

The Railway Cutting SSSI has exposures of the top of the Kimmeridgian, including the local Swindon Clay at the very top, and most of the local Portlandian. The strata dip gently east, so a walk eastward takes one up section. The contact between the Kimmeridge and Portland stages is shown in Figure 4 *(see below)*. The Great Quarry SSSI contains the top of the Portlandian beds, and the Purbeckian. Together they span the late Jurassic into the earliest Cretaceous (Fig. 3, *overleaf*).

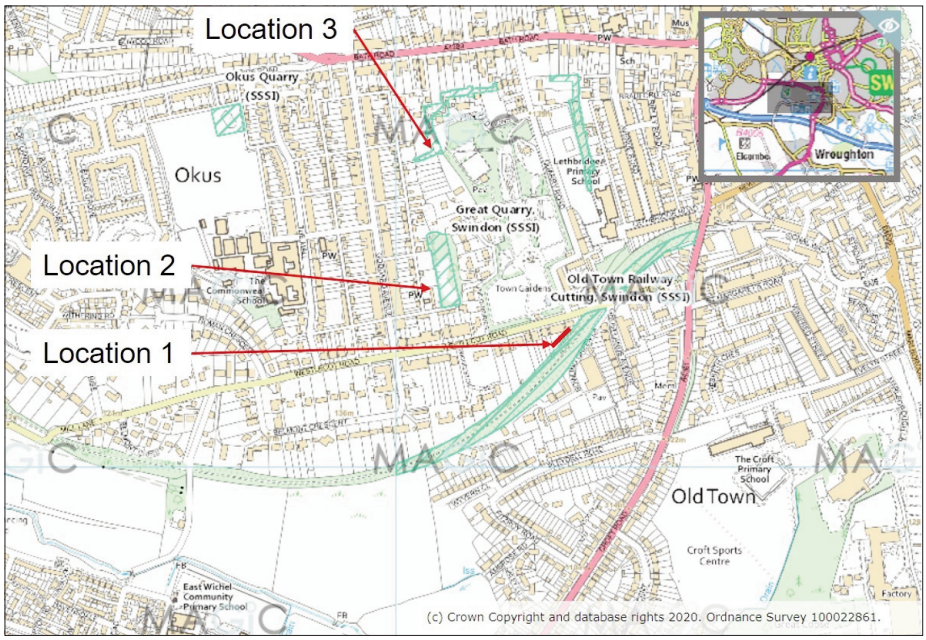

Figure 2 Location of SSSIs on Swindon Hill (© Crown copyright Ordnance Survey. All rights reserved. Reproduced courtesy of DEFRA MAGIC application, Crown copyright: Map produced by MAGIC on [29/11/2020]. Crown Copyright and database rights [2020]. Ordnance Survey 100022861. Copyright resides with the data suppliers and the map must not be reproduced without their permission. Some information in MAGIC is a snapshot of information that is being maintained or continually updated by the originating organisation. Please refer to the documentation for details, as information may be illustrative or representative rather than definitive at this stage).

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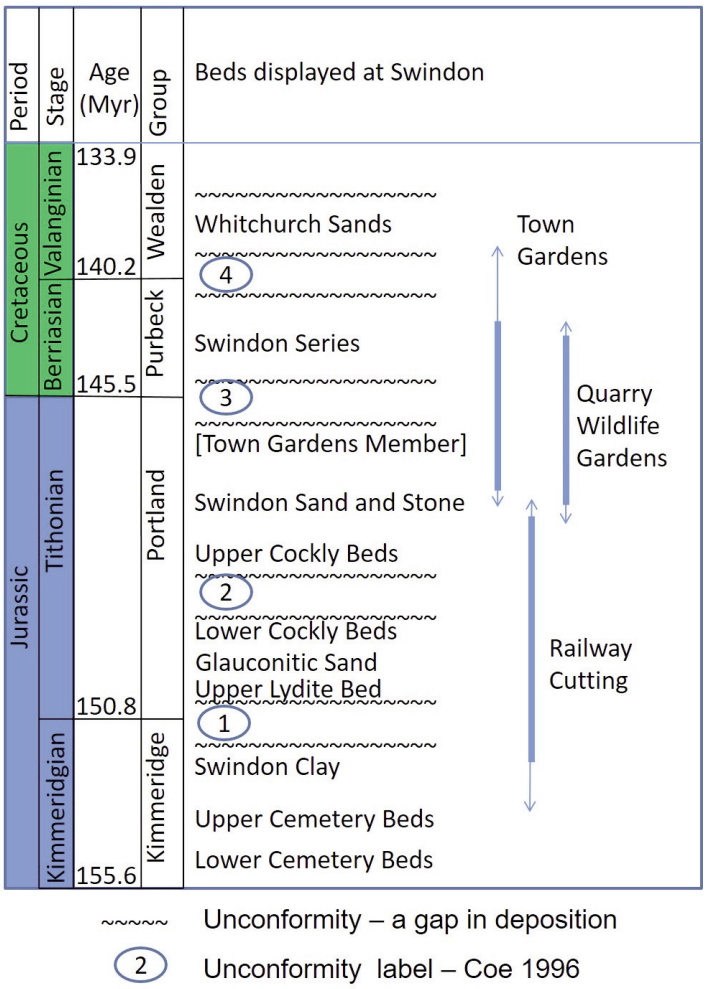

Figure 3 The stratigraphic column displayed in the Railway Cutting and Great Quarry SSSIs.

The position of the Jurassic/Cretaceous boundary has been the subject of much recent research; the Purbeckian beds are now assigned to the early Cretaceous (see e.g. Hopson *et al.* 2008).

These beds span an age range from *c.* 151Ma to *c.* 140Ma, and it is believed that equivalent strata were deposited at Swindon a few Ma before deposition in Dorset. Beds of this age are rare this far north and their facies record changing sea levels in the area.

In the Great Quarry, many formerly worked faces are presently obscured or out of reach, which mean that some beds of the laterally variable Purbeck are unavailable for study.

This location is on the margin between the Wessex Basin and the London platform. Farther south, the basin was subsiding and the sediment piles are thicker. The importance of Swindon as an SSSI is partly because the sediments in Swindon have very different facies, and indicate a provenance from the west (Cornubia) and north-east (London platform), helping to infer tectonic movements in this period.

Description

My description draws on Coe (1996) and references therein. The upper part of the Kimmeridge Group is exposed In the Railway Cutting, which in the south and central Midlands contains frequent sandy lenses (Gallois and Cox 1994). Locally at Swindon, the sand is capped by the Swindon Clay. Above this, the first Portlandian deposit is a pebble bed, known as the Upper Lydite Bed. Coe's Unconformity P1 is between them (Fig. 4). The Upper Lydite Bed contains 10–20mm of rounded polished

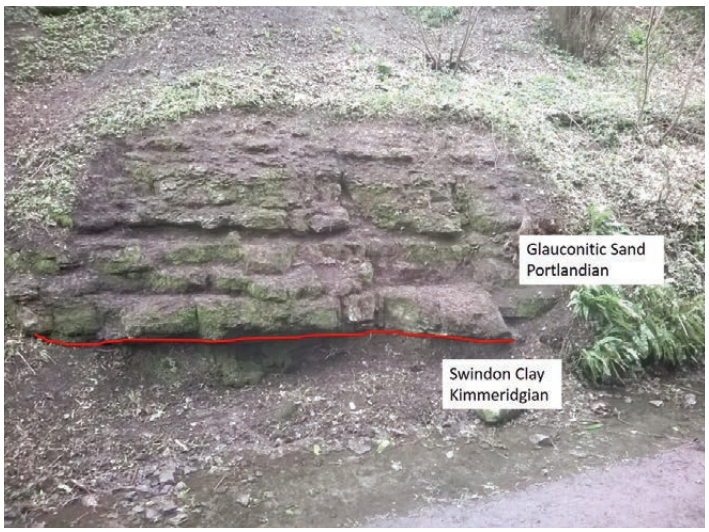

Figure 4 The contact between the Kimmeridge and the Portland at Location 1. The junction is unconformity P1 (Coe 1996) and is a spring line, as suggested by the stream in the foreground (exposure c. *2m high).*

pebbles of vein quartz and Carboniferous chert (lydites), probably reworked from older deposits on the nearby land masses (the London-Brabant massif).

Above the Upper Lydite Bed is the Glauconitic Sand, a sandy micritic limestone rich in glauconite and phosphate, suggesting condensation. The fauna of the Glauconitic Sand includes many thick-shelled bivalves, such as Trigonia, and ammonites indicative of the glaucolithus ammonite biozone.

At Swindon, the Glauconitic Sand is overlain by the Cockly Beds (Fig. 5). These beds of condensed limestone are divisible lithologically and biostratigraphically into two parts. The lower part is a grain-supported bioclastic sand with a micritic matrix. As in the underlying Glauconitic Beds, glauconite, scattered lydite pebbles and quartz sand are present, although they are fewer. Ammonites are common, and indicate the okusensis Zone: this species is named after the Okus Quarry a little farther north-west (*see* Fig. 2).

Unconformity P2 lies above the Lower Cockly Beds. It is followed by the Upper Cockly Beds, which are a micritic limestone-containing, matrix-supported bivalves; large trigoniids and Protocardia predominate. The smaller amount of shell debris and

Figure 5 Unconformity P2 (Coe 1996) is between the Lower and the Upper Cockly Beds (exposure c. *2m high).*

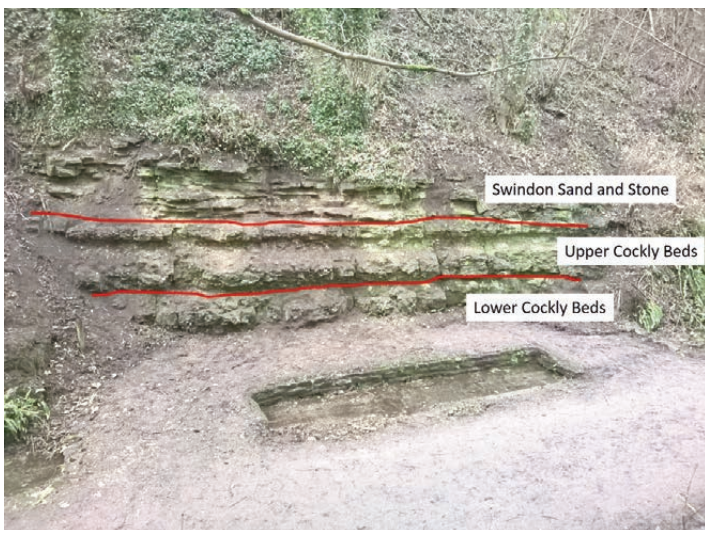

Figure 6 Current cross-bedding in the softer beds of the Swindon Sand and Stone at Location 2 in the Quarry Wildlife Gardens. The sediments are bioturbated by modern small mammals and solitary bees (field of view c. *1m high).*

lack of quartz and glauconite distinguish it from the Lower Cockly Beds. Ammonites indicate the kerberus zone for the upper part. The Cockly Beds grade up into the Swindon Sand and Stone Member, which consists of fine-grained, subrounded to sub-angular, moderately to well sorted sand, with calcareous nodules and bands. The beds show small-scale, low-angle cross-bedding and planar bedding (typical bed thickness is 30mm).

To see farther up the section, it is necessary to go to the Great Quarry SSSI, which spans the Town Gardens park and the Quarry Wildlife Garden, where unconformity P3 is well displayed at two locations and is the boundary between the Swindon Sand and Stone and the overlying rocks. Bedding is well displayed in the softer beds of the Swindon Sand and Stone (Fig. 6). Different beds onlap the erosion surface in different places (Sylvester Bradley 1940). At some places, the Town Gardens Member lies on the Swindon Sand and Stone: but its outcrops are currently not exposed. In the Quarry Wildlife Garden (Location 2 in Fig. 2) the unconformity is gently undulating and overlain by micritic limestones with moulds of tiny bivalves of the younger, non-marine Purbeck Limestone Formation (Fig. 7). The basal few centimetres

Figure 7 Unconformity P3 (Coe 1996). The unconformity surface undulates and here is broken by a pipe (field of view c. *5m high).*

Figure 8 Unconformity P3 (Coe 1996) at Location 3. Here, the unconformity is very sharp and is intersected by quarrying tunnels. The beds in the Purbeck Limestone show in different colours. The layer immediately overlying the unconformity is the Middle Pebbly Bed (Sylvester Bradley 1940) (field of view c. *4m high).*

contain scattered quartz grains, which were probably derived from the Swindon Sand and Stone immediately below.

At Location 3 (*see* Fig. 2) the unconformity is sharp and distinctive: immediately beneath it is the Swindon Sand and Stone, the top of which is enriched with iron minerals and is overlain by the Middle Pebbly Bed (Fig. 8). The pebbles here are very indurated and concentrated in depressions in the unconformity surface (Fig. 9). There are several erosion surfaces within the Purbeck Limestone. Thus the relationship between different beds over short distances is complex. These relationships were illustrated by Sylvester Bradley (1940), but not all those he described are presently visible.

Overall, the rocks at Swindon display varying depositional conditions starting from fully marine in the late Kimmeridgian, through fluvially influenced environments in the Portland, to alluvial and brackish-marine units including evaporite sequences in the Purbeck (Radley and Allen 2012).

Figure 9 A closer view of unconformity P3 (Coe 1996) at Location 3. Immediately above the sharp contact is a pebble lag: the pebbles here are very indurated and concentrated in slight depressions in the unconformity surface. (field of view c. *0.2m high).*

Figure 10 Sarsen stones used decoratively in Greywethers Av., Swindon.

Part 2 Fyfield Down SSSI

History

Fyfield Down is one of the Marlborough Downs and has been occupied since at least the Mesolithic. There are identifiable archaeological remains from every major period since (Fowler 1998). Fyfield Down has one of the densest concentrations of sarsen stones in Britain, although sarsen is distributed over a much larger area (see below). These stones are known locally as 'greywethers' — a 'wether' is a male sheep and the rounded shapes of the sarsens were thought to resemble sheep.

Sarsens have been used in buildings and monuments since the Neolithic period. Spectacular local examples include the Long Barrow at West Kennet and the henge of standing stones at Avebury, which are both Neolithic. In local towns and villages sarsen stones can be seen in field walls and buildings. They are often used in lower courses where their impervious fabric makes them good for damp proofing. For example, they form the foundation layer of the tower at nearby Ogbourne St Andrew church. And Larsen stones are also still used decoratively, for example in the pile in Greywethers Avenue, Swindon (Fig. 10).

Today, Fyfield Down has a unique combination of geomorphological, biological and archaeological features (Natural England 2017). It has multiple protected designations; and it is one of the country's oldest National Nature Reserves, created in 1955. It is a Site of Special Scientific Interest (SSSI) because of the landforms it contains and the wildlife it supports. The whole site is also a Scheduled Ancient Monument and its historical importance was recognised when it was made part of the Avebury and Stonehenge World Heritage Site (Fig. 11).

Thin strips of chalk grassland survive where the soil has been eroded away by carts travelling between Avebury and Marlborough. The exposed chalk provides low nutrient conditions. Elsewhere on the clay soil slopes are small pockets of neutral grasslands, while around the sarsen stones small pockets of acid grassland can be found. The sarsens themselves support a rich lichen flora, including *Buellia saxorum*, which grows uniquely on sarsen stones. These rich flora habitats support a diverse fauna, particularly of birds.

The stones themselves are scattered densely over the hillside in distinctive lateral valley 'trains' formed under periglacial conditions. The various stones record different stages of human interference. Some were polissoirs, used to polish stone implements (Fig. 12). Others were split in linear fashion when stone masons tried to extract them (Fig. 13, *opposite*). Extraction reached a peak in the mid-19th century as hardened steel tools became available and skilled sarsen cutters migrated to the area from the Chilterns, after deposits there had been worked out (Green 2016). After this, the arrival of railways made it easier to import brick for building and use of sarsen declined.

Figure 12 The polissoir on Fyfield Down. The grooves and the dish-shaped hollow to the left were used for polishing stone implements. The stone is no longer in its natural position: part of it was removed in medieval times.

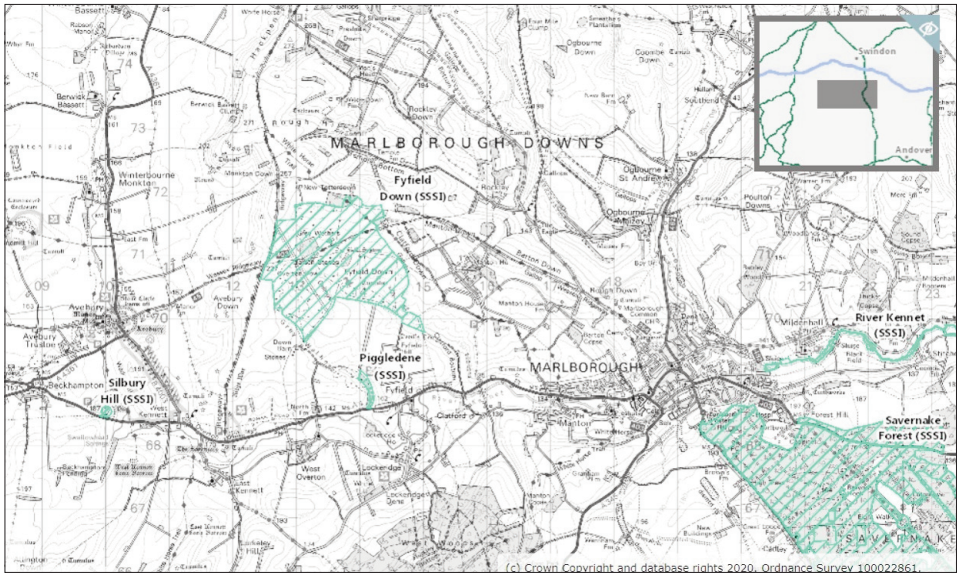

Figure 11 Location of Fyfield Down SSSI, in between Marlborough and Avebury (© Crown copyright Ordnance Survey. All rights reserved;Reproduced courtesy of DEFRA MAGIC).

Figure 13 A split sarsen left in place.

Outline geology

Fyfield Down consists of chalk downland cut with a network of dry valleys. As is typical in much of Wiltshire, the upper parts of the topography are covered by clay-with-flints: the BGS Lexicon of Named Rock Units describes this as a "residual deposit formed from the dissolution, decalcification and cryoturbation of bedrock strata of the Chalk Group and Palaeogene formations … It is unbedded and heterogenous. The dominant lithology is orange-brown and red-brown sandy clay with abundant nodules and rounded pebbles of flint. Angular flints are derived from the Chalk, and rounded flints, sand and clay from Palaeogene formations". The clay-with-flints produces an enriched soil type.

The lower slopes are covered with varied material derived from upslope, variously called 'head', or 'coombe' deposits. The sarsens lie on the surface on the upper slopes, or embedded in the surface deposits lower down (Worsley 2019).

Description

The bedrock at Fyfield Down is chalk: the Seaford Chalk Formation is on the high ground, the New Pit Chalk Formation at the bottom of the valley with the Lewes Nodular Chalk Formation in between them on the slopes (Fig. 14). The traditional boundary between the Middle and the Upper Chalk is about one third of the way up the Lewes Nodular Chalk. The top of the Seaford Chalk (and the base of the clay-with-flints) is believed to be approximately the surface of the early Palaeocene unconformity beneath the Lambeth Group (Worsley 2019). On this surface, on the upper surface of the topography, there is a classic doline (a hollow or basin in a karstic region, typically funnel-shaped) (Fig. 15, *overleaf*).

Sarsen is a hard, silica cemented, fine-to-coarse sandstone, and contains many holes, usually assumed to be root holes. They have long been recognised as the fragmentary remains of more extensive, post-Chalk deposits, although it has been difficult to pin down the exact timings of deposition and silicification. It is now plausibly accepted that they were deposited in meandering river channels as part of the Reading Formation of the Lambeth Group in the Palaeocene, and silicified shortly afterwards during the Palaeocene/Eocene Thermal Maximum, *c.* 55.5Ma (Fig, 16, *overleaf*). Worsley (2019) describes the geology in more detail and includes an account of the history of geological investigation at Fyfield Down.

Sarsens have a fragmentary modern distribution that has been affected by human exploitation, and older OS maps show them as more densely spread on Fyfield Down (Fig. 17, *overleaf*) Summerfield and Goudie 1980). They are the lateral equivalent of the Hertfordshire 'puddingstones', which are a silica-cemented conglomerate. There are similar deposits elsewhere, for example in Dorset and in the Paris Basin. Sarcens are silcretes, which have four main methods of formation (Ullyott and Nash 2016).

Figure 14 Bedrock geology of Fyfield Down (Contains British Geological Survey materials (C) UKRI [2020] Source: https://www.bgs.ac.uk/technologies/apps/igeology-app/ — reproduced courtesy of BGS).

Figure 15 A doline or sinkhole on the relatively flat upper part of Fyfield Down.

Examples of other silcretes around the world are often 'pedogenic', that is, formed in soils or close to a local ground surface. Based on work in the Kalahari, Nash *et al.* (1998) suggest that the Fyfield Down sarsens formed along the sides of drainage channels. Worsley (2019) disagrees, suggesting they are more likely to be groundwater silcretes, a view based largely on geomorphological observations. This latter interpretation seems reasonable. In which case at the time of cementation, groundwater levels were high: silica dissolved at the water table and was deposited as cement when the water evaporated at the surface, forming a silcrete duricrust.

The sarsens are largely grain-supported sandstones with the former voids infilled by optically continuous overgrowths. Their facies varies. Some are a reddish brown, composed of medium to coarse sand with occasional gravel-sized inclusions. They have a relatively immature composition that includes major silica and some feldspar. The colour of the rock is often obscured by extensive lichen growth (Fig. 18). Some sarsens, however, are fine-grained and blue-grey in colour, as in Figure 19 *(opposite)*, which also shows a root hole. This example is atypical of Fyfield Down in that it retains an imprint of what occupied the hole.

There are also many periglacial geomorphological features at Fyfield Down. The modern distribution of sarsens is concentrated in valleys, often in linear 'trains' (Fig. 20, *opposite*). These block runs, similar to those found elsewhere such as in the Valley of Stones near Dorchester or in places on the Falkland Islands, are caused largely by periglacial processes (solifluction), whose effects accumulate with each successive cold stage. It is believed that most of the movement is likely to have taken place in the transition from cold to warm stages, when seasonal melting produced a saturated, wet thin layer on top of a frozen base.

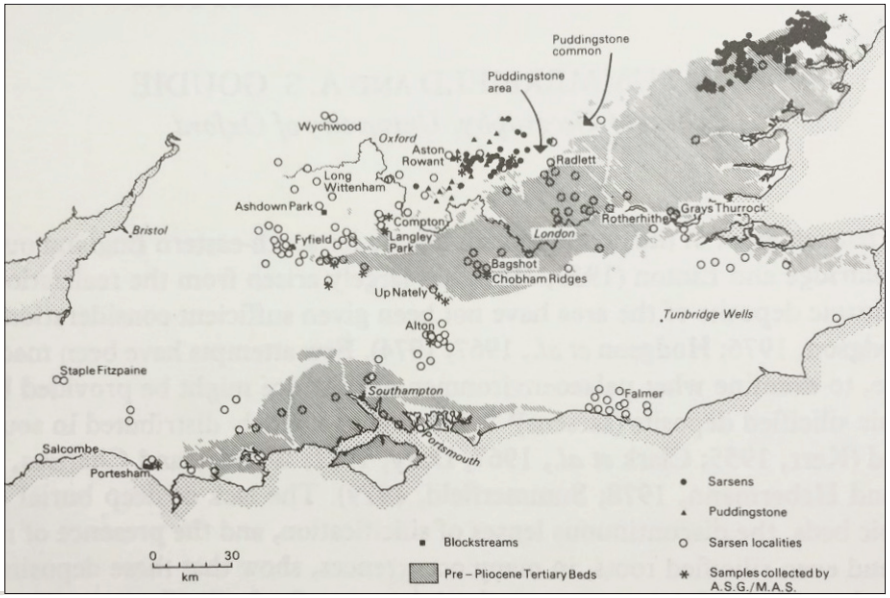

Figure 17 Distribution of sarsens and puddingstones in southern England (Summerfield and Goudie 1980).

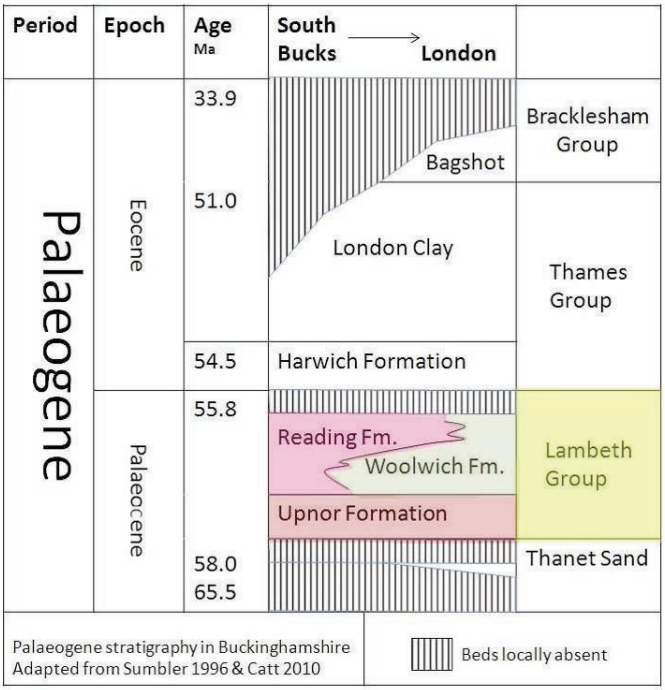

Figure 16 Palaeogene stratigraphy of the area east of Fyfield Down (adapted from Sumbler 1996 and Catt 2010).

Figure 18 A lichen-encrusted sarsen.

Figure 19 A fine-grained, grey blue sarsen containing a plant trace fossil.

Figure 19 also shows a hanging valley leading into the main valley of Fyfield Down, which leads down to Clatford Bottom. The main valley is markedly asymmetrical in section (Fig. 21). This is a commonly found feature of dry valleys in former periglacial environments, although quite how this shape is formed remains unclear (Williams 1980; Whiteman and Haggart 2018).

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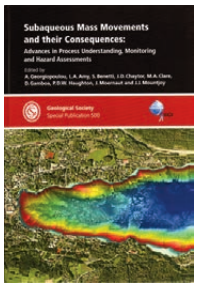
Figure 20 A block train of sarsens running along the bottom of a hanging valley at Fyfield Down. The larger stone at mid-left, the 'Toadstone', is the largest on Fyfield Down.

Figure 21 View along the main valley at Fyfield Down looking south towards Clatford Bottom. The cross-section is asymmetrical with a steeper slope on the right (east).

Book review



Georgiopoulou, A., Amy, L. A., Benetti, S., Chaytor, J. D., Clare, M. A., Gamboa, D., Hanghton, P. D. W., Moerant, J., and Mountjoy, J. J. (eds) 2020 *Subaqueous Mass Movements and their Consequences: Advances in Process Understanding Monitoring and Hazard Assessments*. London: Geological Society of London Special Publication 500 (ISBN 978-1-78620-477-6; ISSN 0305-8719; 539pp; hardback £130)

This special report volume is a comprehensive book on the subject of its title — Subaqueous mass movements and their consequences. The book is divided into four main sections with an introductory chapter, each by a different author:

Section A includes 9 chapters on 'consequences and implications'. Section B has 10 chapters on 'initiation, triggers and preconditioning'. Section C has 10 chapters on 'characterization and regional controls'. Section D has 5 chapters on 'mobility and kinematics'.

At the end of each chapter are acknowledgements, a list of funding contributors and another list of author contributors. The index is extensive; however, a glossary would have been helpful. There are plenty of comprehensively annotated illustrations, graphics, cross-sections, maps, figures, tables and diagrams — many in colour.

The book opens with the 2018 Christmas tsunami and the collapse of Anak Krakatoa in Indonesia, with both sub aerial and subaqueous slope failures.

The 2016 Kaikoura NZ earthquake also triggered a seafloor failure. Gullies in Cook Strait near the crest of the slope seem likely to have been formed by downslope acceleration of fluid or gravity flux. Submarine landslides can occur anywhere there is an inclined seafloor. Such sediment movements form mass transport deposits of up to thousands of square kilometres and thousands of metres of thickness. Both sediments and underlying basement rocks may be mobilised.

The gullies in Cook Strait seem likely to have been formed by downslope gravity flows.

Glacigenic lakes in the Eastern Alps are useful for smaller-scale studies of lacustrine landslides, with accurate backdating of events and space/time distribution of mass transport deposits.

Melting ice sheets cause rising land levels, together with deposition of debris, pushed downslope towards the seabed. Liquefaction can occur when the air trapped in soils is replaced by water. This was evident in the 2010–11 Christchurch earth movements, in which at least one vent was big enough to sink a vehicle.

Submarine slope failures may be due to clay content posing risks to coasts and causing earthquakes and tsunamis. Plate subduction can cause greater seismic activity, deformation and tectonic activity, and submarine landslides. However, the 2016 Kaikoura NZ quake triggered slope failure, but not tsunamis. The New Zealand Alpine fault extends the whole length of South Island, across Cook Strait and north-eastwards into the Pacific through Rotorua, with submarine landslides possible the whole length of the east coast of both islands where the Pacific Plate subducts under the Australasian plate. These landslides can occur on gentle slopes and may depend on the sediment composition.

Submarine mass transport deposits have been identified off the coast of Donegal in western Ireland, and off Rockall, and are associated with ice sheet dynamics.

Movement of mudflows down the Mississippi River, together with steep ocean floor slopes, are recognised hazards to the oil and gas industry platforms in the gulf of Mexico.

— Rosemary Darby, OUGS, BA (Open), BSc Hons (Open) Natural Sciences with Earth Science, Certs Ed UK & NZ

Clashach Quarry and its trace fossils

David Longstaff

Clashach Quarry is a mile east of Hopeman village on the south side of the Moray Firth. The geology is cross-bedded sandstones attributed to the late Permian Period. The site was declared a SSSI by Scottish Natural Heritage (site reference No. 361) because it provides an excellent section through the Hopeman Sandstone Formation, continues to reveal Permian reptile footprint trackways and was also the find site of a dicynodont fossil skull in 1997 (Figs 1 and 2).

Geology

The sandstones are aeolian in origin, with large sets of cross-bedding visible in places, and belong to the Hopeman Sandstone Formation (Fig. 3). The sand grains are well sorted and rounded with in a non-calcareous cement varying between quartz (giving a hard, siliceous sandstone) and iron oxide (giving a more friable sandstone). This variability from different areas of the quarry has had consequences for the suitability of the stone for use as either a quality building stone with a range of colours from buff to yellow to pink, being used for millstones, or simply being crushed for use as an aggregate. The building stone is known to be resistant to weathering and acid rain damage, and also has a high resistance to salt damage (Building Research Establishment 2000).

A south-dipping, east–west-running fault, formed during Late Jurassic development of the Inner Moray Firth (Woma 2014), runs through the quarry. Until a few years ago it effectively formed the southern back wall of the quarry with slickensides with minor mineralisation, still visible in small areas. Recent quarrying has moved south, through the fault zone, and the southern boundary of the quarry is now close to the Moray Coastal Trail.

The sandstones were laid down in a desert or semi-arid environment, at a paleo-latitude of *c.* 20˚ N, with evidence of ephemeral streams having existed in the area. Examples of ripple-marked sandstone and slumped, wet sand deformation features can be found on the foreshore *c.* 400m west of the quarry. A reptile trackway here, impressed in the damp sand, was vandalised abouit 1995 and the remnants removed to the Museum of Scotland where a slab in on display. Paleo-wind indicators show that the prevailing wind was from the north-east, with secondary winds coming from the south-east. The large-scale cross-bedding found in the quarry has foreset dip angles of up to 26˚ to the south-west. Ventifacts, including Dreikanters, are often found, confirming the desert-like environment present in the geological past.

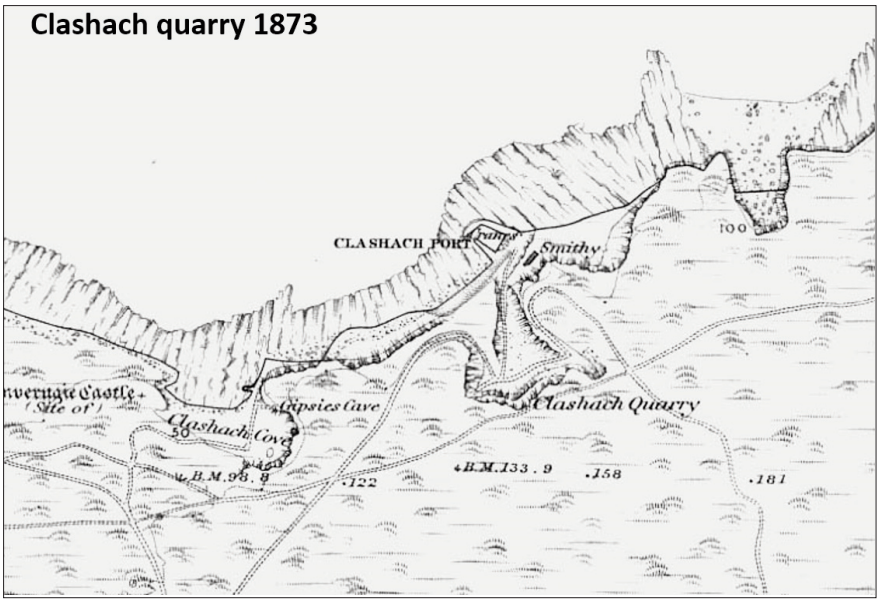


Figure 1 Map of Clashach Quarry in 1873 (reproduced with the permission of the National library of Scotland).

The deposits are regarded as an onshore equivalent of the Rotliegend gas reservoir beds of the Southern North Sea and, as such, are regularly studied by geology students; and until recently, because of the lack of identifiable body fossils, the Hopeman Sandstone Formation was always dated as being Permo-Triassic.

(see below)

Figure 2 Clashach Quarry in 2019, looking south.

Figure 3 Example of cross-bedding in old Clashach Quarry.

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Quarrying

As with other quarries in the Elgin area quarrying at Clashach has occurred for hundreds of years. Documentation is sparse, but there are mentions of quarrying, for example, in old local newspapers, including advertisements of quarries for rent.

It is not known when quarrying started in the region, but it has been suggested that quarrying took place in medieval times (Oram 1996). It is thought that Duffus Castle, built in the 12th century, used stone from the local coastal quarries. There are records of nearby Covesea quarry being used for building stone as far back as 1639 (Douglas 1928). Covesea stone was used in the building of Fort George in 1748 and of the Falconer Museum in Forres. Other buildings or structures that have used Clashach stone include, Elgin Sheriff Court, King's College chapel Aberdeen, the SAS memorial in Hereford Cathedral, Covesea Skerries lighthouse and, in 1998, 1,500 tons of Clashach stone were used in the facing of the Museum of Scotland.

On the international stage the 9/11 memorial in New York, opened in 2011, used Clashach stone (*The Northern Scot* 2018), and over the last two years the quarry has seen a period of increased production due to demand from Spanish builders completing the building of the Sagrada Familia in Barcelona. A Spanish stonemason visits the quarry once or twice a year and selects the desired blocks, which are then transported south. An article from *The Scotsman* newspaper from July 2006 gives more detail: "Mr Baillie explained that the quarry secured the lucrative contact after Moray Stone Cutters supplied sandstone for work on the nearby Barcelona Cathedral last year. Architects working on the La Sagrada project noticed that the stone, used in the construction of the cathedral, closely resembled the stone from a now-unworked Catalonian quarry[,] which had originally been used in the construction of Gaudi's masterpiece".

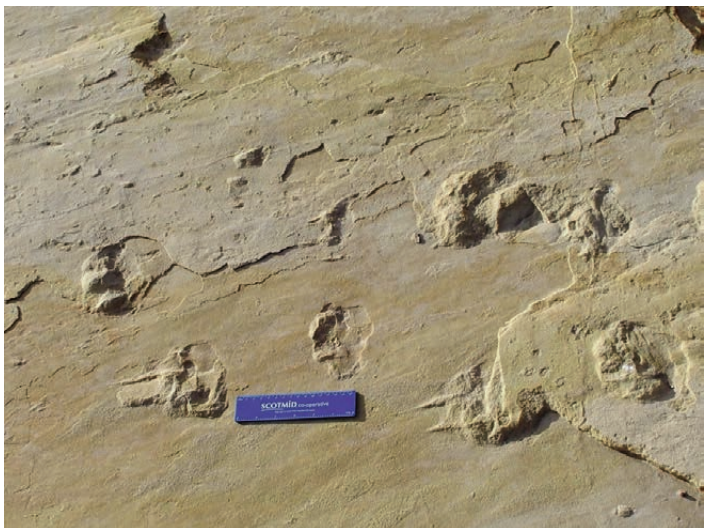
Clashach port and old Clashach Quarry

A harbour was built to allow the sandstone blocks to be transported away from Clashach by means of boats — see the top of the 1873 map shown in Figure 1. First discussed in 1777 by Sir William Gordon and a Mr Kyle, Hopeman harbour was built *c*. 1836–38 under the instruction of Admiral Archibald Duff, and a small port was built near Clashach soon afterwards. An advertisement from the *Forres Gazette* for 18 October 1857 reported, "There is a convenient and safe harbour at the principal quarry, sufficient to admit vessels of 100 tons burden; and by means of railway crane and wagons stones of any size may be conveyed from the quarry to the ship…at a trifling expense." (Bartlam 2001).'Port Clashach' was used until the early 1900s when, seemingly, it was allowed to fall into disrepair. It is thought that the arrival of the railway to Hopeman in 1892, passing directly beside another sandstone quarry, Greenbrae Quarry, hastened the temporary closure of Clashach Quarry and the demise of the port. (McPherson 2008). Apparently, there was a tramway from the quarry down to the port, but nothing is left of this structure today. Any evidence may be buried under a huge pile of waste rubble below the current quarry. However, long-disused trackways, for horse and cart, can be seen to the south-east of the old harbour, and small portions of the pier walls can still be seen (Bartlam 2001), although accelerated erosion of the pier has been noticed in the past 30 years. There are two inscriptions dated 1781 in a corner of the disused quarry — high on a back wall above the old port, giving an idea of when the old quarry was in operation (Fig. 4). As well as displaying historic quarry pick marks, the footings of a blacksmith's shop, mason marks and old graffiti of this long-disused quarry has superb examples of sandstone cross-bedding and is often visited by university geology students.

Trace fossils

Fossil reptile footprint trackways were first reported from the coastal quarries, mainly at Maisonhaugh and Greenbrae, by Capt. Lambert Brickenden in 1850. Brickenden thought they were made by a tortoise, hence the generic name of 'Chelichnus' was given to the fossil footprints. Examples are shown in Figures 5, 6, 7 and 8 *(opposite)*. Many of these 'rabbit footprints', as the quarrymen called them, were found in these quarries and, apart from a small fragment of unidentifiable bone found in Greenbrae Quarry, were the only fossils thought present in the coastal sandstones. Fossils found inland from the same formation at Cutties Hillock had mostly come from the base of the formations, and it is thought that the lack of exposure of this part of the succession along the coast accounted for the apparent lack of the fossils (Peacock 1968). Preservation of animal body parts depends on the ambient conditions at the time of death: there seems to have been a difference between Cutties Hillock (near Elgin) — where we find both footprints and bone — and Clashach — where even the dicynodont skull is only identified as a mould (Benton and Walker 1984).

Figure 4 Detail of cross-bedding, Clashach port old quarry, and the '1781' graffito carved into the hard, siliceous sandstone on the back wall.



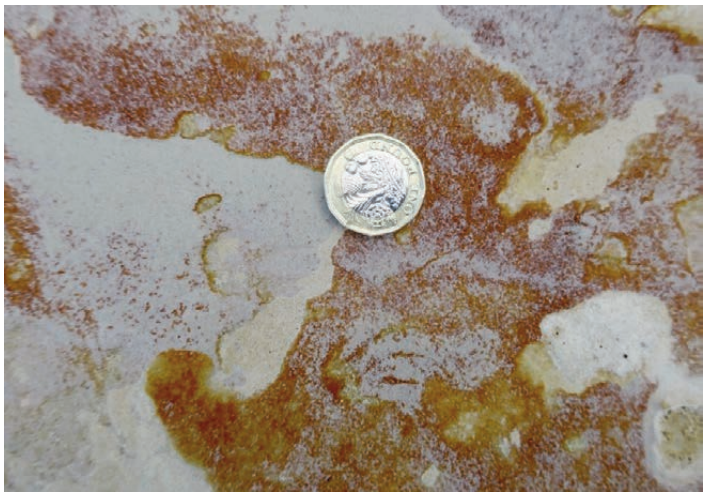
Figures 5–7 (above and below rught) Examples of the various sizes and types of dicynodont footprints found at Clashach Quarry.

These quarries closed in the 1970s, leaving only Clashach Quarry, and nearby Spynie Quarry (Triassic), continuing to produce sandstone.

Quarrying operations were increased in 1996 to provide stone for the new National Museum of Scotland and during this period many reptile-footprint-bearing slabs were exposed both on quarried blocks and *in situ*. Carol Hopkins, an OU student living in Hopeman, made a systematic survey and recorded *c.* 400 trackways in the quarry. One slab found *in situ* on the then floor of the quarry was already well known about. The prints on this slab are *c.* 100–150mm wide and have been made by one of the larger-sized animals, most probably a dicynodont.

Dicynodonts were herbivorous reptiles living throughout the Permian Period and, indeed, some species survived the Permian/Triassic extinction event. These animals possessed no teeth, they had a beak-like jaw with two tusks hence — the name dicynodont "Two dog tooth"— and are regarded as stem mammals (formerly termed mammal-like reptiles) (Fig. 9).

The slab was uplifted in 1998, in two parts, in advance of the quarry's downward extension and was removed to a public display area just outside the quarry beside the Moray Coastal Trail. The display contains about a dozen blocks showing a variety of types of fossil footprints, but is now heavily covered with lichen;

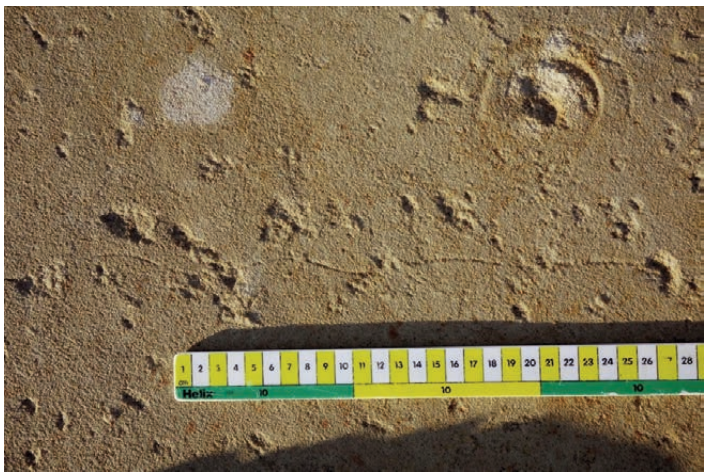


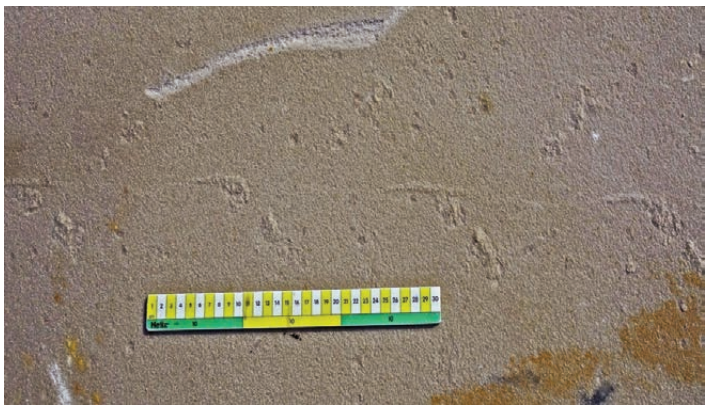
and nearby gorse growth needs regular pruning, as it threatens to overrun the display area.

Ever since trackways were found in the Cummingston quarries there was anecdotal evidence that the tracks always seemed to be heading north — to presumed water or vegetation in what is now the Moray Firth basin, probably to a former desert lake or playa. Evidence from Clashach confirms this suggestion; and there is similar evidence for Permian animals in the Dumfries area having

Figure 8 Trace fossil of a small reptile trackway.

Figure 9 Reconstruction model of a dicynodont climbing a dune, leaving characteristic footprints with a short stride length, Burghead Beach, Grampian.





Figures 10 and 11 Examples of tail-drag trace fossils.

made their tracks heading south to the Solway Firth. Apart from the broken slabs found in the quarry floor most of the larger trackways are from 1m to 4m long (Hopkins 2007). Currently all the tracks in the quarry are found on broken metre-sized blocks, with actual bedding planes almost never being revealed. Unfortunately, this removes any context to show the direction the animals were travelling, the angle of slope of the fossilised dune or the stratigraphic level in the quarry.

McKeever and Haubold (1996) argue that the prints relate to one ichnogenus Chelichnus and four inchnospecies, and that many of the differences in the Clashach sandstones were due to variation in gait and angle and condition of the dunes themselves. Although tracks may be preserved as digitigrade (toe) or plantigrade (sole) impressions with up to five digits visible, the digitigrade stance had not evolved by the Permian, so apparent digitgrade tracks in the quarry are due to incomplete preservation of the track. An interesting aspect of the fossil footprints is the number and variety of reptile tail-drag traces to be found, some tails being dragged continuously through the sediment and some only touching the sand intermittently. Such differences are interpreted as the result of the type of reptile producing the tail-drag, the angle of ground traversed and the speed of the animal. The width of tail-drag markings never exceeds 10mm, and is often much narrower, and seems to have been made by small reptiles (Figs 10 and 11).

There is a wide range of both size and type of fossil footprint to be found at Clashach Quarry. Considering that the environment was of a semi-arid region there seems to have been quite an abundant fauna living near by or passing through the area, although not necessarily all at the same time. There was moisture present and, indeed, the foreshore near Clashach shows evidence of running water; so at the very least, ephemeral streams must have run through the dunes. However, despite dicynodonts being herbivores no fossil plants have ever been found. Invertebrate traces are also present, consisting of vertical or horizontal burrows up to 1m long, supporting the idea that the sediment must have been moist at times. Some of these trace fossils are undoubtedly of worms, while others display features that resemble backfilling of sediment such as that of a beetle, or something similar, working its way through the substrate (Figs 12 and 13, *opposite*). One particularly unusual trace fossil, the only example of its type seen by the author, consists of a series of zigzags thought to be created by a beetle larva (pers. comm. Prof. Luis Buatois, University of Saskatchewan). Interestingly, the Permian Corncockle Sandstones of Dumfries and Galloway are also famous for their reptile trackways of fauna similar to those of the Clashach reptile tracks, but lack any evidence of invertebrate trace fossils (McKeever 1991).

Discovery of dicynodont fossil skull and the dating of the sandstone

As mentioned, the age of the Clashach deposits had always been described as Permo-Triassic, but this changed with the discovery of a dicynodont skull in the quarry in 1997. The subsequent investigation of the fossil is an unusual and important story in the dating of the Hopeman sandstones (Clark 2008). Previously the only body fossil found in the coastal quarries was an unidentified fragment of bone found in nearby Greenbrae Quarry during a geological survey *c.* 1996 (Peacock *et al.* 1968).

In 1997 a quarryman noted an unusual hole in a sandstone block and alerted the manager Drew Baillie and OU student Carol Hopkins. It was hypothesised that the cavity might be a fossil mould and Dr Neil Clark, Curator of Palaeontology at the Hunterian Museum at University of Glasgow, was informed. Clark took the block to the university, where it was subjected to Computed Tomography (CT) scanning and Magnetic Resonance Imaging (MRI). Scanning revealed the void of an un-deformed skull and lower jaw of an animal. Using the digital data recovered enabled a life-sized, 3-D model to be made of it. The blocks containing the voids, cast of a humerus and an improved 'lifelike' skull and lower jaw are all in Elgin Museum. After analysis, the fossil was shown to be similar to a known dicynodont, *Gordonia traquairi*, found in Permian sandstones at Cutties Hillock quarry near Elgin. The Clashach dicynodont is named *Dicynodon traquairi* (Cruickshank, Clark and Adams 2005). For the first time the Hopeman Sandstone Formation at Clashach Quarry could be accurately dated as Late Permian, *c.* 250Ma.

Access to Clashach Quarry (NJ 162702)

This is summarised in: Schedule for accessing, reporting, recording, researching, and possible retrieval for safeguard, of important fossil interest within Clashach Quarry, Hopeman, Moray. SNH April 2015. Permission for access must be obtained from the quarry operators, Tennants Ltd, Elgin, www.tennantselgin.com

Remember to follow the Fossil Code:
https://www.nature.scot/scottish-fossil-code

Figure 12 Fossil worm traces at Clashach Quarry.

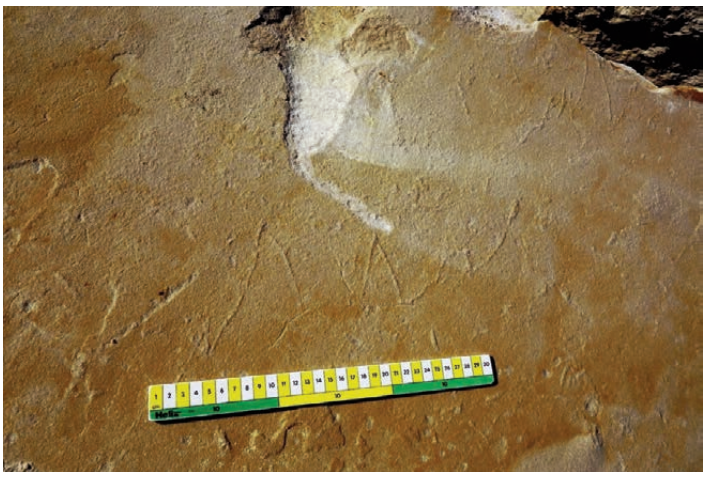


Figure 13 Unusual arthropod trace at Clashach Quarry — possibly a beetle larva.

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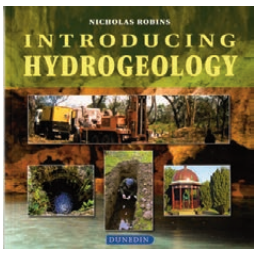
Book review



Robins, Nicholas 2020 *Introducing Hydrogeology*. Edinburgh: Dunedin (ISBN 978-1-78046-078-9; 108pp; paperback £14.99; also pdf 978-1-78046-626-5 pdf, e-pub 978-1-78046-616-3 and Amazon Kindle 978-1-78046-617-0)

I agree with Jane Michaels' review in *OUGS Proceedings* 5, 2019, of *Introducing Metamorphism* (in the same series from Dunedin) as to the attraction of this short book. In pre-OU days I was taking modules for an external London degree, one of which was Hydrology, so I have some background in the subject.

The book is divided into 12 chapters, and has a Preface, Glossary and further reading list.

As stated in the Preface, the book is intended to be an introduction rather than a textbook, and explores many topical issues, including water shortage and climate change.

Yet again Dunedin has a success. It is beautifully illustrated with photos, diagrams and charts, including material from the USGS and worldwide examples.

The chapters are:

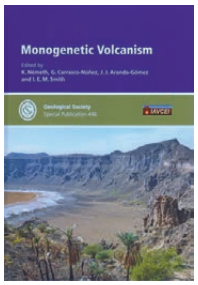
1 Water, Earth's special mineral
2 Aquifers and the three Rs — rainfall, runoff and recharge
3 Aquifer properties and groundwater flow
4 Groundwater flow and numerical analysis
5 Boreholes and test pumping
6 Groundwater management
7 Groundwater quality
8 Groundwater pollution, vulnerability and protection
9 Coastal aquifers and small islands — a challenge
10 Flood, drought and subsidence
11 Some topical issues
12 Hydrogeology.

The last chapter asks, "What does a hydrogeologist do? When did the science begin?", and says that today it is still an imperfect science.

I enjoyed reading this book and would recommend it for interest.

— Rosemary Darby, OUGS, BA (Open), BSc Hons (Open) Natural Sciences with Earth Science, Certs Ed UK & NZ

Book review



Németh, K., Carrasco-Núñez, G., Aranda-Gómez, J. J., and Sith, I. E. M. (eds) 2017 *Monogenetic Volcanism*. London: Geological Society Special Publication 446 (978-1-78620-276-5; 388pp; hardback £110)

The volume, *Monogenetic Volcanism*, is a collection of 14 papers published by the Geological Society of London under an agreement with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). It has arisen from IAVCEI Commission on Monogenetic Volcanism, as stated inside the front cover of the book. The volume contains papers on various aspects of monogenetic volcanism (defined as 'fields of small volcanoes, each the product of a temporally restricted eruption of a compositionally distinct batch of magma' (Smith and Németh 2017, page 1 in the abstract of the first paper in *Monogenetic Volcanism*).

The initial paper gives an overview of, and introduction to, monogenetic volcanism. The following papers are loosely arranged into groups, starting with three papers on the emplacement and growth of maar-diatreme volcanoes, scoria cones and kimberlite pipes.

Following the establishment of these general principles, there are two long papers (each *c.* 50pp), each of which gives a thorough review of a volcanic field. The areas and age of volcanics reviewed are the Newer Volcanics Province, south-east Australia, and Late Quaternary volcanism in northern Harrat Rahat, Kingdom of Saudi Arabia. A single paper examining the Tango Extension Super Structure in Canada is next. There is then a group of four papers reviewing maars and volcanic centres in Mexico, two of which are paired and deal with Isla Isabel.

A group of three papers about volcanism in South America completes the volume. All of the papers on south American volcanism follow the same general format, although they discuss different geographical areas; two pertaining to the Puna region of Argentina (north and south), the third to central Columbia.

The papers, taken as a whole, appear to give a good overview of the current knowledge of monogenetic volcanism, and the research being undertaken in different parts of the world into the processes involved. The scope of research contained within this volume varies from a thorough review of a large area (e.g. Cas *et al.* on Newer Volcanics in south-east Australia) to very detailed investigations into a smaller area (e.g. Fulop and Kurszlaukis on the Tango Extension Super Structure).

The volume is well illustrated throughout with relevant diagrams, both colour and black and white, maps, tables and photographs (including some thin sections and SEM photography). In some instances, though, the figure is in black and white, but colours are referred to in the figure's caption, which can be confusing. It is left to the reader to infer which shade of grey corresponds to the colour mentioned in the text. This may be a function of the publishing process, as a polygon in one paper is referred to in the caption as blue, but appears in the figure in pink (pp298–9). This is not difficult to overcome, but something to be aware of when studying the figures. It is also noticeable that there are some typographical errors and that Fig. 3 (p7), in particular, lacks clarity in the caption that explains it.

The majority of the papers in this collection would probably be accessible to a keen volcano enthusiast with a good geology dictionary to hand. A few are technical and might be of greater interest to those studying or researching the areas under discussion.

The physical book is in standard Geological Society Special Publication format: a good quality hardback measuring 175mm ¥ 253mm (slightly smaller than A4), with semi-glossy paper. It is possible to make, and carefully erase, light notes in pencil on the paper. There is a contents page at the beginning with the authors and titles of each paper; and each submission is followed by a full reference list. A single index is comprehensive.

Deborah Parke, BSc (Hons) Natural Sciences (Earth Sciences)

Acid rock drainage and acid mine drainage: processes, effects and practical studies

Chris Popham

Acid rock drainage is the process by which sulphide minerals decompose when exposed to oxygen to yield aqueous acidic products. As mining frequently exposes sulphides and the workings underground require dewatering, the resultant acid mine drainage may become large-scale and problematic.

Sulphide mineral deposits such as pyrite (FeS_2) are naturally stable in the ground below the water table, where conditions are anoxic. Should the water table be lowered due to mining or excavation, the depletion of aquifers, or through geological processes such as uplift or erosion, as examples, then oxygen-mediated sulphide decomposition might occur.

Pyrite has two chemically identical isoforms: the brassy, cubic form often termed Fool's Gold, which is relatively stable, and the soft and gritty form known as marcasite, which can rapidly decompose.

Where oxygenated water is the medium, the decomposition of pyrite can be expressed in the following way:

$$2FeS_{2(s)} + 7O_{2(g)} + 2H_2O_{(l)} \eth 2Fe^{2+}{}_{(aq)} + 4SO_4{}^{2-}{}_{(aq)} + 4H^{+}{}_{(aq)}$$

The decomposition may be mediated by micro-organisms able to take advantage of the energy released by the reaction.

The resulting acidification of the water by the dissolved hydrogen ions facilitates positive feedback by further oxidation of the iron (II) ions:

$$4Fe^{2+}{}_{(aq)} + 2O_{2(g)} + 4H^{+}{}_{(aq)} \eth 4Fe^{3+}{}_{(aq)} + 2H_2O_{(l)}$$

And subsequent reduction of the iron (III) ions:

$$2FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{(l)} \eth 15Fe^{2+}(aq) + 2SO_4{}^{2-}{}_{(aq)} + 16H^{+}{}_{(aq)}$$

If sufficient acidification occurs, ancillary mineral sulphides such as galena (lead), chalcopyrite (copper) and sphalerite (zinc) will also decompose along with ores of cadmium and nickel, all of which yield highly toxic metal ions in solution.

As natural geological processes advance at slow rates, however, and as water flow is usually unimpeded, the resulting acidification is typically low-level over a prolonged period of time and yet quickly dispersed. Consequently, decomposition of ancillary sulphides may not occur, and if it does the products are often secondary minerals: cerrusite (lead), malachite (copper) and smithsonite (zinc), rather than dissolved ions.

In mines, however, there may be a rapid exposure of large mineral reserves, breathable air must be brought underground and water is invariably present. Furthermore, the co-deposition of low-value iron sulphide alongside other high-value metal sulphides may result in underground stockpiling of mixed sulphide wastes.

Nevertheless, during the active life of a mine dewatering may result in only low levels of acidification and the outflow of water is typically managed through settling ponds, where lime is used to reduce the acidity causing metal ions to precipitate, or metals are removed by biological filtering systems that are tolerant to the toxicity. The resulting pond slurry and/or biomass can then be safely managed and may have a residual value depending on the metals present.

When mines fall idle, however, underground lakes and reservoirs may form in which the acidity becomes remarkably high and into which copious quantities of metal-ion slurry settles. Left unmanaged, the reservoir dams may eventually fail, resulting in a discharge of acidic, metal-ion-rich water and slurry into watercourses.

In the south-west of England perhaps the most notorious event in relatively recent times occurred in Cornwall at Wheal Jane in 1992 when an estimated 50 million litres of water and slurry discharged into the Carnon River over several days. In the 1960s, and again in 1993, smaller events occurred at the Cwm Rheidol group of mines in Ceredigion, with resulting pollution of the Afon Rheidol; and in 2008, for a number of days the River Tamar downstream of Gunnislake on the Devon-Cornwall border was turned bright orange by discharge from an unidentified source.

The effect of such mass discharges into watercourses is invariably catastrophic. In the first instance the water suffers severe oxygen depletion leading rapidly to the death of all aquatic animal life. The slurry will settle onto plant life, choking and poisoning it, a process that is exacerbated if the acidity of the discharge is neutralised, whereupon the metal ions will precipitate as hydroxides.

The settled slurry will retain the metal ions for an extended period, much to the detriment of invertebrates, which often burrow into riverbeds. The reduced invertebrate biomass not only constricts the food supply for vertebrates such as fish, but the passage of zinc, copper and cadmium metal ions through the food chain is detrimental to the gills of fish, reducing their ability to survive in poorly oxygenated water. Additionally, lead causes bone and fin malformation in fish. Passing further along the food chain to birds and mammals, the metal ions reduce fertility and result in birth defects or non-viable embryos.

Controlled management of discharges may be costly, and in the case of abandoned mines in the UK that cost inevitably falls on the public purse. The settling ponds and on-going treatment and disposal of outflow from Wheal Jane in the 10 years after the 1992 event is thought to have cost upwards of £20m. At Cwm Rheidol the discharge of water is controlled, but the treatment involving beds of limestone chips proved poorly effective, as the chips quickly became coated with insoluble calcium sulphate. Wetland 'reed bed systems' are effective, but only after pre-treatment of the water; and it is important that the resulting biomass is removed or remains submerged where decomposition results in an oxygen-free environment. If not, the metal ions may become remobilised. An extensive wetland scheme is active at Force Crag Mine in Cumbria.

Case Study 1: Wheal Exmouth

The dumps of this abandoned lead mine near Christow in Devon contain galena, pyrite and arsenopyrite. Not only are there dumps on the bank of the River Teign, but between 2008 and 2012 a drainage scheme was put in place to dewater an adit and this produces a constant untreated discharge into the river (Figs 1a and 1b, *overleaf*).

Water in both the adit and dump discharges is mildly acidic (pH 5.76).

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Figure 1a Clear discharge from the spoil mixing with iron tainted discharge from the adit.

Figure 1b Untreated discharge into the River Teign.

800ml of adit discharge was filtered, and the particulate material retained. Addition of a small amount of sodium carbonate to 200ml of the clarified water raised the pH to 9.56 and within a few minutes the water had taken on a brown tint compared to an untreated sample (Fig. 2). After three hours the carbonate-treated sample had produced a fine, light-brown deposit in the beaker, while the untreated sample remained clear. Sodium, not calcium carbonate, was used to exclude the potential for insoluble calcium sulphate precipitation:

The reactions of iron (II) ions with carbonate are as follows:

$Fe^{2+}_{(aq)} + CO_3^{2-}{}_{(aq)}$ ð $FeCO_{3(s)}$ (a white precipitate)

Dissolved oxygen will further the reaction:

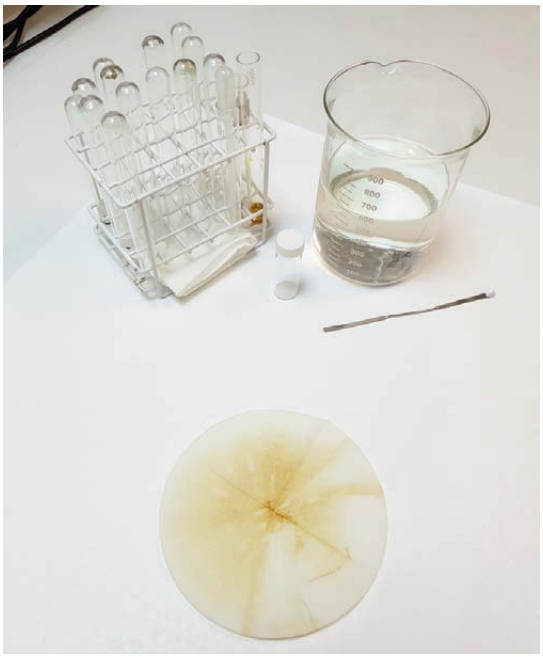
$FeCO_{3(s)} + O_{2(g)} + 3H_2O_{(l)}$ ð $HCO_3^{-}{}_{(aq)} + 2OH^{-}_{(aq)} + Fe(OH)_{3(s)}$ (a brown precipitate)

Iron (III) ions will not react directly with dissolved carbonate, but rather as follows:

$CO_3^{2-}{}_{(aq)} + H_2O_{(l)}$ ð $HCO_3^{-}{}_{(aq)} + OH^{-}_{(aq)}$
$Fe^{3+}_{(aq)} + 3OH^{-}_{(aq)}$ ð $Fe(OH)_{3(s)}$

As both iron (II) and iron (III) ions will ultimately produce a brown precipitate in the presence of dissolved oxygen, a further sample of the filtered water was placed under vacuum in a stirred vessel until no further gas exsolved. The ‘deoxygenated’ sample was transferred to a smaller bottle containing a little sodium carbonate, with the headspace filled with pure nitrogen. After about an hour a white precipitate began to form, and overnight this settled as a thin layer on the bottom of the bottle. The contents were then filtered and the paper gradually turned

Figure 2 The solids from 800ml of discharge collected on a 100mm filter paper.



Figures 3a (left) and 3b (right) Pebbles coated with copper carbonate.

brown in the presence of oxygen, indicting — as predicted by the preceding equations for the decomposition of pyrite — that the water was rich in iron (II) ions.

Acidification of some of the particulates collected from the initial filtering with 0.01M hydrochloric acid (pH <2.0) produced no effect, whereas similar treatment with 0.01M sulphuric or nitric acids slowly dissolved the solids, as expected.

Case Study 2: Gawton Mine

This mine is situated beside the River Tamar and was renowned for having a pool of blue water where run-off from the dump collected, although this has quite recently been breached and drained. However, the bed of the outflow stream from the dumps is thickly populated with bright green pebbles (Figs 3a and 3b).

The stream water is mildly acidic: pH5.52; and addition of sodium carbonate to filtered water produced a slight off-white (not brown) precipitate. When the precipitate was dissolved in nitric acid and the product treated with ammonia a slight blue 'diaqua' copper result was observed. However, if nitric acid is used to dissolve the coat from pebbles a green solution results, which turns a vivid royal blue colour on addition of ammonia. The pebbles are lime-rich country rock onto which copper carbonate continues to precipitate due to the change from acid to alkaline conditions 100 years after the mine was closed.

The recovery of copper

Iron is more electropositive than copper — or, simply put, iron has a greater affinity for negatively charged ions than does copper. Consequently if the acid discharge from a mine or tip contacts a source of negative ions such as the carbonate ions in limestone, then the limestone will dissolve due to the acidity, and the iron will precipitate as outlined above in preference to the copper ions. One outcome, therefore, may be that the water draining from the mine becomes depleted in iron, while relatively enriched in copper. On the evidence above, this appears to be the case at Gawton Mine.

This difference in electropositivity may, however, in theory be utilised to extract copper from the discharge.

One account is of the activities of one John (aka Jack) Cloke, a former mine worker in the 1920s. It is said that, with or without permission from several landowners in the Gunnislake area, who had abandoned mines on their property (Devon Great Consols and Gawton are specifically named), Cloke worked discharges from the mines for copper. This was simply achieved by exploiting the difference in electropositivity of metals and placing scrap iron in the water onto which copper would accu-mulate, a process that is occasionally observed in abandoned mine workings if water contacts abandoned iron items.

To investigate the validity of this process a short length of iron-mine tram rail was suspended in a stream running from under the Gawton Mine dump at a suitable spot.

After eight months the rail was taken out of the water and the rusty surface was observed to be coated with a grey deposit. Once dried, the grey-white bloom was more apparent (Figs 4a and 4b, *overleaf*).

Washing a small area with dilute nitric acid produced an olive-green solution; and neutralising that with ammonia produced the telltale royal blue colour indicating the coating was copper (Fig. 5, *overleaf*).

The green coating was similarly dissolved off the surface of stream pebbles using 10% aqueous solutions of either nitric or sulphuric acid. In both cases this produced a dark-green solution with a pH of *c.* 1.4.

Treating the copper solutions with either sodium hydroxide or sodium carbonate raised the pH to *c.* 4.5 and produced a highly viscous olive-green precipitate of the sort seen as a brief interim product during the ammonia neutralisation process. The viscosity hindered any further pH neutralisation. The precipitates re-dissolved on acidification.

Figures 4a and 4b The iron rail fresh from the water and later dried in the sunshine.

Carbon electrodes connected to a 12V battery, constantly charged by a solar panel, were suspended in some of the nitric acid solution (Fig. 6). Gasses were evolved at both electrodes and the positive (anode) electrode was slowly eroded. Meanwhile, copper was deposited on the negative (cathode) electrode as a peach-coloured coating and lumpy masses. Carbon was used initially to mitigate metal-ion contamination from the sacrificial anode and because the copper is visually apparent on the black carbon of the cathode.

Figure 5 Royal blue 'diaqua' copper test.

Replacing the carbon cathode with a strip of copper again saw copper from the solution deposited as a peach-pink surface, and lumpy masses that could be washed off with clean water and collected (Figs 7a and 7b, *opposite*).

Figure 6 Electrolysis arrangement.

Figures 7a and 7b Copper deposited on a carbon electrode and collected in a dish.

This adequately demonstrates the natural enrichment of copper in the mine run-off and that it can be collected on surfaces and subsequently recovered. At this stage, however, it is unclear how Jack Cloke went about recovering copper as an economically viable process from the iron scrap he used (Fig. 8).

Sources

Information display board at Cwm Rheidol Mine.
Wikipedia.org.
https://projects.exeter.ac.uk/geomincentre/estuary/Main/jane.htm (valid July, 2020)

An additional note on testing for copper with ammonia

The above account mentions a royal blue 'diaqua' copper colour in several places as a positive test for copper. Starting with chalcopyrite ore the test can be summarised as follows:

$CuFeS_{(s)} + 10HNO_{3(aq)} \rightarrow$
$[Cu(H_2O)_6]^{2+}(NO_3^-)_2$ (hexaqua copper (II) ion)$_{(aq)}$ +
$[Fe(H_2O)_6]^{3+}(NO_3^-)_3$ (hexaqua iron (III) ion)$_{(aq)}$ +
$5H_2O_{(l)} + 5NO_2$ (brown fumes) + $S_{(s)}$

The resulting solution will have a pale blue-green tint.
Then with pH neutralisation with ammonia:

$[Cu(H_2O)_6]^{2+}{}_{(aq)} + 2NH_{3(aq)} \rightarrow [Cu(H_2O)_4(OH)_2]_{(s)}$
(a pale green passing to blue interim precipitate) + $2NH_4^+{}_{(aq)}$

And then with excess ammonia:

$[Cu(H_2O)_4(OH)_2]_{(aq)} + 4NH_{3(aq)} \rightarrow [Cu(NH_3)_4(H_2O)_2]^{2+}{}_{(aq)}$
(the royal blue coloured tetraaminediaqua copper (II) ion solution) + $4H_2O_{(l)}$

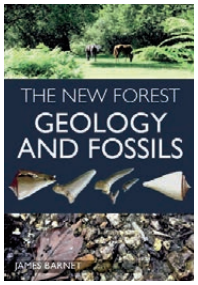
And:
$[Fe(H_2O)_6]^{3+}{}_{(aq)} + 3NH_{3(aq)} \rightarrow [Fe(H_2O)_3(OH)_3]_{(s)}$
(a brown precipitate) + $3NH_4^+{}_{(aq)}$

The royal blue end colour solution is a reliable test for copper from most mineral sources.

Source:
http://www.chemguide.co.uk/inorganic/complexions/aquanh3.html (valid July, 2020)

Figure 8 Failed treatment process at Cwmrheidol Mine: fairly clearly the water is passing through three large ponds, but at the lower right corner heavy iron staining of the wall and colour in the water shows the untreated discharge entering the river.

Book review



Barnet, James 2021 *The New Forest: Geology and Fossils*. Ramsbury: The Crowood Press Ltd (ISBN 978-1-78500-816-0; 178pp; paperback £16.99)

Dr James Barnet (MSc Geology, University of Southampton; PhD Geology, University of Exeter) grew up in the New Forest, and has been studying its geology and fossils for 30 years.

His opening chapter describes the New Forest, briefly summarising its environment, history and establishment as a National Park. In his own words, his book "aims to be the most complete and up to date guide to the geology and fossils of the New Forest National Park and surrounding area".

The first chapter, 'Geological history of the New Forest National Park' (about one-third of the book) is a descriptive geology of the NewForest from the Permian Period to the present, setting it into its wider context within the geology of southern England. The text is brief and to the point, enhanced and amplified with 81 figures: geological charts, chronologies, stratigraphic maps, palaeogeographic maps, explanatory cartoons, photographs of exposures and outcrops, and photographs of fossils. His text is clear and concise.

Chapter 2 is more specific, about the geology of petroleum exploration and extraction from the Wessex and Weald basins. It too is, replete, with useful maps and other illustrations.

Chapter 3, 'Palaeogene stratigraphy of the central and eastern Hampshire Basin, including the New Forest National Park', more specifically sets the geology of the New Forest into its wider context. With detailed graphs of boreholes and lithological sequence logs, Barnet takes the reader on an armchair field trip to exposures and outcrops to explain stratigraphic and tectonic developments over the past 65 million years, mostly concentrating on the 43Ma period of the Palaeogene.

Chapter 4, 'Natural resources within the New Forest National Park and surrounding area', is a brief (four pages) description of the region's resources: ironstone, aquifers, geothermal energy, sands and gravels, marl and clay (including brick- and tile-making clays), and extractable peat.

Chapters 5, 'Fossil hunting in the New Forest National Park', and 6, 'Fossiliferous sites in the Hampshire Basin outside the New Forest', provide guides to the best places to see — and sometimes collect — fossils in the two areas covered by the book. For example, in Chapter 5, a detailed map shows the locations of Eocene exposures, which underlie almost the entire News Forest. Chapter 6 concentrates on the beach and cliff exposures of the south coast.

Chapter 7, 'The Fossils of the New Forest National Park' (about one-quarter of the book) is a photographic catalogue illustrating and describing types and species, providing a clear and practical guide to New Forest fossils. In the author's words, "a comprehensive illustrated guide of the most abundant fossil species at Studley Wood and Bramshaw". The excellent photographs will enable fossil hunters to identify any finds, either in outcrops or for collection.

Most chapters, in addition to their abundance of illustrations*. have occasional grey boxed special topic sections, providing more specific details on subjects such as 'sedimentary sequences', the Kimmeridge oilfield and petroleum explorations from the 1960s, fossil collection advice and 'rules', essential fossil collecting equipment, and the care and preservation of fossils.

Barnet firmly discourages 'digging' for fossils, and encourages proper respect for fossil sites and SSSIs.He advocates only collecting already eroded, loose specimens; or sometimes washing and sieving stream gravels for loose fossils. — see Chapter 5's grey box section on fossil hunting and collecting "rules and advice".

The final Chapter 8 is a guide to resources for the 'amateur geologist': local societies and websites.

The book is completed with a five-page Glossary of geological terms, a four-page Bibliography, and a short Index.

Dr Barnet's guide is a handy and well written book that any geologist — professional or amateur — interested in Palaeogene life will find informative and of practical use.

* There are 144 excellent colour photographs, and with the other figures 198 illustrations in total, all in colour — yes, I counted them.

— Dr David M. Jones, OUGS Proceedings Editor

The marble tomb of Archbishop Tait

Geoff Downer

"...every precious stone was thy covering..."
Ezekiel 28:13 (King James Edition)

A marble is not only a metamorphosed limestone, but in the building trade is the term used for a decorative stone that will take a good polish. Metamorphism is the process of changing a rock's character through the addition of heat, pressure or fluid composition. The terms stone and marble are often used interchangeably in the following account and a reference to a geological marble is noted as such. The conventions of capitalising names of specific marbles and italicising non-English names has been used.

Archibald Campbell Tait was born in Edinburgh and graduated with a first class degree at Oxford. During the reign of Queen Victoria he rose through the tiers of the Church of England and was consecrated Archbishop of Canterbury in 1868. He was seen very much as an evangelist and often had to tread the middle ground during a period of numerous religious controversies. This gained him much respect from his contemporaries. He passed away on 3 December 1882 at Addington, South London.

Archbishop Tait was buried in St Mary's the Blessed Virgin Church in Addington at the request of his family. Nearby Addington Palace was the summer residence of the Archbishops of Canterbury between 1808 and 1897 and six 19th-century archbishops are buried there. Over the next few years steps were taken to place appropriate memorials to the late archbishop in Westminster Abbey, Rugby School Chapel, in Edinburgh and, most sumptuously, in Canterbury Cathedral.

To help decide upon a suitable memorial a local Tait Memorial Committee was established at Canterbury, but in mid-1883 it decided to postpone coming to a decision until the National Memorial Fund's trustees were prepared to change their commemorative plans.[1] The national committee preferred a recumbent figure while the local preference was for the memorial to take the form of a reredos. In April 1884 a way forward was found and the Dean and Chapter finally agreed to a tomb chest with effigy located in the north-east transept of the cathedral (Fig. 1). The Chapter Act Book for 1884 verifies that the design of John Oldrid Scott was approved, "excepting the steps". It was thought a tomb chest with steps would be "occupying too large a space & [the Dean and Chapter] preferred the alternative design for the platform. In the design for the platform [it was] recommended that in place of the inlaid patterns, slabs of coloured marble be used".[2]

The Archbishop Tait Memorial Fund raised the sum of £11,863, although some donations continued to arrive after this total was recorded. The Canterbury Diocesan Gazette noted the expenditure and listed the donors. The sum of '£2388 10s 0d' was used to pay for the Canterbury memorial. Most of the remaining money in the fund paid for other national Tait memorials or was used for Mission purposes to promote various evangelical works that would have met with the late Primate's approval.[3] At the unveiling (4.00pm on 20 October 1885), "the present Archbishop [Edward Benson], and the Bishop of Dover, spoke on the occasion. The Archbishop expressed himself in terms of high praise of the memorial as 'not unworthy of so great a shrine' "[4]

Figure 1 The Tomb of Archbishop Tait in the North East Transept of Canterbury Cathedral, photographed facing south-west. The principal marbles are identified (height 1.68m, width 1.44m, length 2.77m).

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FARMER & BRINDLEY, Ltd., Sculptors, Carvers, Marble Quarry Proprietors, Merchants and General Marble Contractors, Workers in Wood and Stone; Museum of Marble and Ancient Monuments, 63, Westminster Bridge Road, London, S.E. *Hours of Business:* 9 a.m. to 5 p.m.; Saturdays, 9 a.m. to 12 noon. *Established* over sixty years ago by the late William Farmer. The founder was joined in partnership in 1869 by William Brindley, who had been in his employ from the commencement of the business. *Incorporated* in 1905 as a private Limited Company. *Managing Director:* William Brindley. *Directors:* H. W. Barnes, E. R. Brindley, A. C. Brindley. *Premises:* Works, &c., extending to over an acre of ground. Firm are proprietors of valuable marble quarries. *Staff:* From 300 to 500, according to requirements. *Specialities:* Sculpture and Carving, particularly in rare marbles; also in Wood and Stone. Representative firm in this branch of art industry. Have executed very fine work in innumerable public buildings. *Connection:* World-wide. *Telephone:* No. 2396 Hop.. *Telegraphic Address:* "Farmer Brindley, London." *Cable Address:* "Porphyry, London."

Figure 2 Archbishop' Tait's tomb was a relatively early commission for William Brindley following the death of his partner; the firm of Farmer and Brindley continued to develop until the outbreak of World War I. This advert for the firm appeared in Whitaker's Red Book of Commerce or Who's Who in Business, *published in 1914. The firm of Farmer and Brindley had been incorporated in 1905 (source of cutting:* Grace's Guide to British Industrial History*).*

The north-east transept can be a rarely visited corner of the cathedral, but just a few paces off the normal tourist ambulation will bring the visitor to the splendid freestanding tomb chest monument of Archbishop Tait with reclining effigy. More accurately the structure should be referred to as a cenotaph, as no physical body is housed within.

The Tait monument is made from several cut and polished stone slabs with much inlay marble work; that is the technique of inserting cut pieces of coloured stone into shallow depressions with a flush surface to produce a decorative effect. Decorative inlay marble workmanship, such as we see in this tomb, is sometimes referred to as *pietra dura*. However, this term is more appropriate for siliceous materials as it is Italian for 'hard rock' and broadly all the inserts in this tomb are limestones or geological marbles.

The tomb monument was designed by John Oldrid Scott, upon which rests a sleeping effigy carved by the sculptor Sir Joseph Edgar Boehm; the effigy is 'signed' at the foot where the pall has been gathered: *J. E. Boehm Fecit*. The Victoria and Albert Museum has in its possession a plaster cast made by Boehm of the clasped hands of the archbishop 'moulded from nature after death', presumably in preparation for the carving of the effigy.[5] It is therefore likely that a death mask was created at the same time to serve as a sculptor's model, but this has not survived.

The 'architectural portion' (i.e. the tomb chest and pediment) was constructed at a cost of £825 under the direction of William Brindley of 'Farmer and Brindley' (Fig. 2).[6] By 1885 Brindley was the sole proprietor of the firm, his partner William Farmer having died in 1879. The partnership had specialised in architectural sculpture and ornamentation, but by 1881 Brindley had expanded the ornamental stone side of the business and was describing the firm as Stone and Marble Merchants.[7] Over the next two decades he was to tour the Mediterranean region in search of marbles used in classical times, rediscover Roman quarries and negotiate for the transportation of a new supply of decorative stone to England. In correspondence he was described as "know[ing] more about marble quarries than any man living".[8] His "intimate knowledge of antique marbles and other ornamental stones" was rewarded in 1888 when he was elected a Fellow of the Geological Society of London and was recognised by the society as a leading authority in matters relating to ancient architecture.[9] The firm's numerous executed works included the decorative sculpture on the Albert Memorial (1863–1875) and the models for the terracotta decoration on the Natural History Museum in South Kensington, London (1873–1881).[10]

The stone for the effigy was sourced from a newly opened quarry using Seravezza marble; marble (1) below.[11] Bracketed numbers (1 to 13) refer to the marbles detailed below in this account. The stone used in the construction of the Archbishop's tomb was recorded in *The Builder* as "pavonazzo" (2), "breccia" (3), "deep red Rosso marble" (4) and a "dark green porphyry" (5).[12] Unfortunately the inlay marbles are not named in *The Builder* article, but these are examined below following a description of the above five materials.

(1) *Seravezza Statuario*

The effigy of Archbishop Tait has been carved from a single block of exceptionally pure, translucent *Seravezza Statuario* (Fig. 3). The Seravezza quarries of Monte Altissimo in the southern Apuan Alps of Italy are located only 20km south-west of the more renowned Carrara quarries. With the close proximity of the two quarrying areas it is no surprise that the marbles are not unalike and have experienced a similar geological past. The Seravezza quarries date back to 1517 (although local tradition dates them to the 14th century) when documentation evidences that they were opened up to provide marble for Michelangelo Buonarroti for the facade of San Lorenzo of Florence. All the white statuary marble produced from these quarries during the 16th century was for the sole use of the Medici family, the local community having donated the mountains of Ceragiola and Altissimo to the city of Florence. *Seravezza Statuario* has also been referred to as *Statuario Altissimo* and *Seravezza White Marble*.

Figure 3 The head, upper body and folded hands of Archbishop Tait in Seravezza Statuario.

Figure 4 The tomb plinth in Breccia Pernice, *composed of numerous, angular pieces of limestone and cemented by a sometimes violet-coloured (haematite-enriched) carbonate cement (north east corner of tomb).*

Quarrying on the mountainside has been discontinuous since the 16th century. In 1884, when the tomb was being carved, the local industry was vibrant. The total workforce employed at the time was 1,480 with 680 working in the Seravezza quarries, 180 transporting the stone, 360 employed in the sawmills and 260 in the sculptural workshops. Situated within the Apuan Alps Park, environmental controls are today more stringent and active quarries are few and production intermittent. *Seravezza Statuario* can often be visually indistinguishable from Carrara Marble; in the absence of a known source only detailed isotopic analysis of certain constituent elements can usually demonstrate provenance.

(2) *Pavanazzo*

The chest tomb itself is constructed of several pieces of grey-veined white marble (Fig. 1). The white marble can be seen to be yellow-hued in places and the grey veining sometimes to be violet in coloration. These colour ranges are due to the different quantities of metallic oxides present. The name *Pavanazzo* is a descriptive name and derives from the Italian word for peacock (*pavone*), whose coloured plumage the marble is said to resemble. The marble is variegated and can have a much greater colour range than seen on this tomb.

Pavanazzo is one of the many varieties of Carrara Marble, and is the name given to identical-looking marbles from the quarries at Seravezza (*see* stone (1) above). During the formation of the Apuan Alps the rocks were subjected to intense deformation causing the brittle carbonate rock to fracture and develop cracks providing channels for mineralisation and thereby create the veining that is the characteristic feature of this decorative stone. When working the marble it is the veins that are often the principal lines of weakness and, as a result, great care needs to be taken when cutting the stone. Renwick states that by 1909 "*Pavonazzo* is only found in 'pockets' and is consequently variable both in supply and quality." He goes on to say "At the time of writing this marble is very scarce and of comparatively poor quality."[13] Thankfully there is nothing in this monument to suggest that William Brindley procured poor quality stone 25 years earlier.

Pavonazzo has also been used extensively in Westminster Cathedral and there are further examples in the frontage of the Adelphi Theatre, Strand and the impressive staircase in the Rosewood Hotel, London. The stone described here should not be confused with a similarly named stone from Afyon in Turkey called *Pavonazzetto* (*see* stone (11) below).

(3) *Breccia Pernic*e (the breccia)

A breccia is a rock consisting of angular or subangular fragments. It can be of sedimentary, igneous or deformational origin. It is a generic term and does not assist much in identification of the stone's provenance. The breccia referred to in *The Builder* must be that which adorns the tomb plinth.

This marble that makes up the plinth is composed of angular fragments ranging in colour from pink-white to deep-red-pink and is most likely to be the Lower Jurassic Italian breccia known as *Breccia Pernice* (Fig. 4). *Pernice* is Italian for partridge and the stone's colours were once considered to resemble the bird's plumage. The rock fragments are all limestones of different hues depending on the quantity of iron oxide and iron hydroxide present. The material cementing the limestone blocks is also calcium carbonate. The rock fracturing took place during the formation of the Alpine mountain range.

The quarries are located at Monte Pastello near Fumane in the Veneto. The stone is sometimes also known as *Breccia Fumane* and in the past as *Occhio di Pernice* when it was quarried from the region of Valpantena, also to the north of Verona. The stone is used for interior designs, such as pavings, fireplace facings and kitchen surfaces. The quarries are still active today.

(4) 'deep-red Rosso Marble'

The epitaph for the tomb was provided by the Dean of Llandaff and appears as letters of gold on a centrally located red marble side panel on the north side of the tomb (Fig. 5, *overleaf*). On the opposing side, in the same position, is a brief biography of Archbishop Tait, inscribed on an identical red marble (Fig. 6, *overleaf*). Elsewhere on the tomb pieces of inlay in the same red marble provide a colourful embellishment. *The Builder* magazine's description "deep-red Rosso marble" is a purely descriptive term and gives no information about provenance, although implying a continental source. There are numerous varieties of

A GREAT ARCHBISHOP
JUST, DISCERNING, DIGNIFIED, STATESMANLIKE
WISE TO KNOW THE TIME AND RESOLUTE TO REDEEM IT
HE HAD ONE AIM
TO MAKE THE CHURCH OF ENGLAND MORE AND MORE
THE CHURCH OF THE PEOPLE
DRAWING TOWARDS IT BOTH BY WORD AND GOOD EXAMPLE
ALL WHO LOVE THINGS TRUE AND PURE
BEAUTIFUL AND OF GOOD REPORT

ARCHIBALD CAMPBELL TAIT
BORN DEC 21ST 1811.
DEAN OF CARLISLE 1849.
BISHOP OF LONDON 1856.
ARCHBISHOP OF CANTERBURY 1869.
DIED ADVENT SUNDAY, DEC. 3, 1882.

Figure 5 (left) A central side panel of Rosso *marble; note the use of inlay marble around the stone inscription (field of view: 0.48m ¥ 0.48m, north side of tomb).*

Figure 6 (right) A central side panel of Rosso *marble with brief biographical details of Archbishop Tait; note the use of inlay marble around the stone inscription (field of view: 0.42m ¥ 0.42m, south side of tomb).*

red marble from England and the continent; most are limestones rather than true geological marbles. The identity of "deep-red Rosso marble" is yet to be confirmed from appearance alone, but may be the marble known as *Rosso Antico* quarried from Greece or from Turkey.

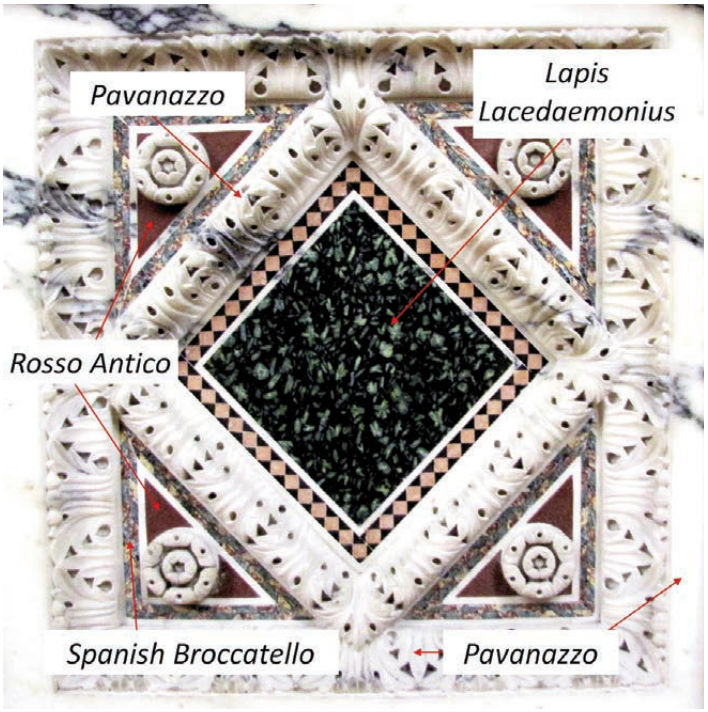
In support of an argument for the stone to be a Greek *Rosso Antico* the following is worth noting. In 1851 the Greek Government despatched from Skoutari, "three pieces of the Rosso Antico, used by the ancients for sculpture and architecture"[14] for presentation at the Great Exhibition in Hyde Park, London, following the rediscovery of the quarries in 1829 by a French expedition and a later visitation in 1850 by a German geologist. The stone came from the newly re-opened quarries on the Mani Peninsula on the southern coast of Greece. Warren records several architectural works in England between 1869 and 1882 using *Rosso Antico* from Mani, including the marble decoration of Saint Sophia Cathedral, the Byzantine Greek Orthodox church in Bayswater installed in 1881–1882 by Farmer and Brindley. William Brindley was therefore familiar with the marble at the time of the Tait commission. Farmer and Brindley later begun to import their own *Rosso Antico* in 1887 and continued to do so until 1920 or shortly after, having become the quarry proprietors in 1899.[15]

Although *Rosso Antico* ('ancient red') has been quarried since the Bronze Age it was during classical Roman times that the decorative stone came into its own for both architectural features and sculptural work. The stone is a true metamorphic marble having recrystallised from a marine limestone of Eocene age. The grains of calcite are coated with finely dispersed haematite (and manganese) giving the marble a hue that can range from pinky-red to purple. It has been used as a decorative stone in many church buildings, notably St Paul's Cathedral (1871–1888) and Westminster Cathedral (1901–1961). Confirmation of this attribution is, however, still awaited.

(5) *Lapis Lacedaemonius* (the dark-green porphyry)

Four diamond-shaped side panels made from a 'dark-green porphyry' adorn the tomb (Fig. 7). A porphyry is any igneous rock that has large, well-formed crystals embedded in a fine-grained groundmass. The large crystals are known as phenocrysts. The 'dark-green' porphyry in the tomb is unusual in that the phenocrysts are an apple-green colour and are set in a similar groundmass of much smaller crystals with an overall darker-green appearance.

Figure 7 A side panel of Lapis Lacedaemonius*; note the use of* Rosso *marble inlay in the four 'spandrels' (field of view: 0.48m ¥ 0.48m, north side, west end of tomb).*

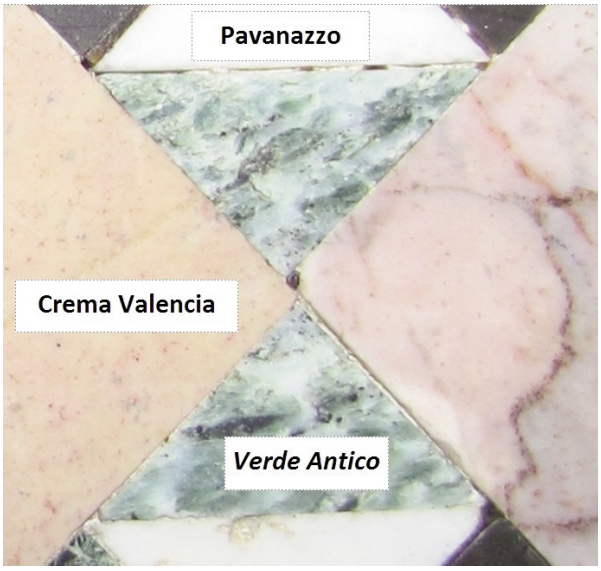


This distinctive stone is Lapis Lacedaemonius from Krokeai (formerly Levetsova) near Sparta, Laconia, Greece — a subduction related calc-alkaline rock of Triassic age. It can be categorised as an altered (by low-grade metamorphic and metasomatic processes) porphyritic basalt/andesite. It consists of large lath-shaped subhedral plagioclase phenocrysts within a fine-grained groundmass that includes devitrified glass and the breakdown minerals epidote and chlorite, which give the stone its green colour. The feldspar phenocrysts are often aggregated, giving the stone a glomeroporphyritic texture that has formed by the attachment of crystals to each other through surface tension and subsequent interpenetration as the crystals grow — a process called synneusis. Plagioclase often shows a pervasive alteration into sericite (a variety of muscovite mica), calcite and clay minerals. This would account for the colour change to yellow in many crystal interiors.[16]

The stone is known by numerous other names, including *Krokeatis lithos*, *Marmor Lacedaemonium*, *Porfido verde antico* and Ancient Green Porphyry. During the 1st and 2nd centuries AD the Romans quarried and exported Lapis Lacedaemonius to Italy for the manufacture of household ornaments and to decorate buildings. Blocks of the stone were limited in size and rarely exceeded one square metre. Consequently examples of its use are usually restricted to small items. After the Roman period the quarries remained inactive and later medieval use of the stone was as a result of Roman spolia. In the 19th century the quarries were rediscovered by French explorers. Examples of *Lapis Lacedaemonius* can be seen in and on the interior pavement in Westminster Cathedral.

The inlay marbles present in Archbishop Tait's tomb chest are not referred to by name or description in *The Builder* article of 24 April 1886. We are simply informed that the "work is very richly inlaid and carved". There are eight different stones used for inserts, that is, small cut pieces of marble used for inlay work (Fig. 8); a red-veined pink-yellow marble (6),

Figure 8 A detail of Pavanazzo, Verde Antico, Black Marble *and* Valencia Marble. *Between the marble inserts a very fine lime mortar has been used, upon which each stone is also carefully bedded. In places the mortar can be seen to have come loose. There is no record in the Cathedral Archives of any restoration to the tomb having taken place (field of view: 25mm ¥ 25mm).*



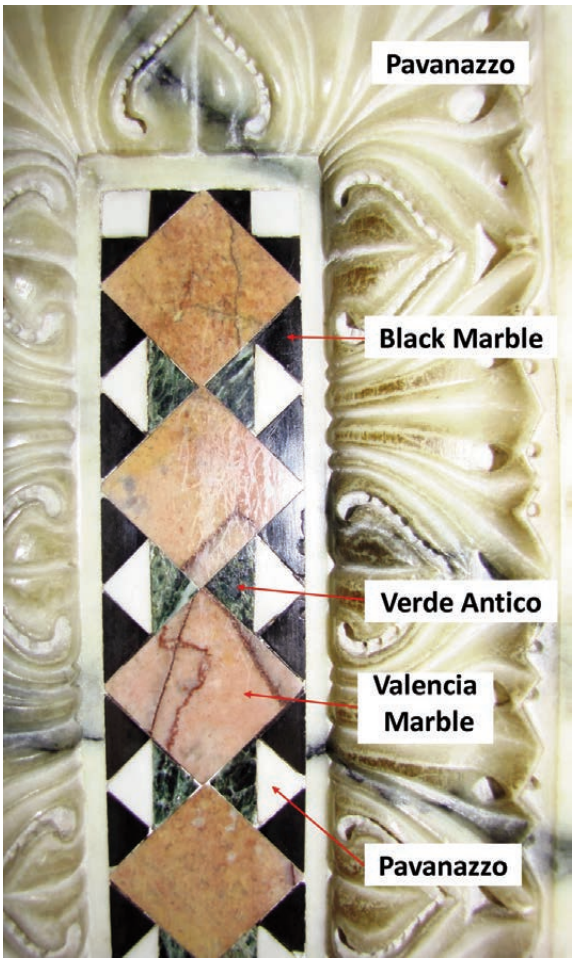


Figure 9 Diamond-shaped Valencia Marble *inlay (field of view: 60mm ¥ 180mm, west side, south end of tomb).*

a green-grey marble (7), a variegated red-yellow marble (8), a yellow marble (9), a brecciated green marble (10), a white and violet breccia (11), a white marble (12) and a black marble (13). A brief description and the most likely provenance are provided below for each of these stones.

However, a word of caution should be applied. Not all of the materials used by William Brindley to manufacture the stone inserts may have come direct from the original source quarry. Brindley, who constructed the tomb, was known to collect Roman and Greek marble spolia on his Mediterranean travels and he was not averse to using recycled classical building material on his various architectural projects.[17]

(6) *Valencia Marble*

There are a number of diamond-shaped, pink-yellow marble inserts encircling the four pieces of *Lapis Lacedaemonius* (Fig. 7) and located on the end side panels (Fig. 9).

This marble is predominantly pink in colour with yellow undertones, more apparent on some inserts than others and through some pieces runs a deep-red veining. A stone that matches this description that was on the market in England in the late 19th century is *Valencia Marble*. The stone has been marketed under various names, including *Crema Valencia* and *Rosa Valencia*, distinguishing the yellow and pink varieties retrospectively; most inserts of this type could be classified as *Rosa Valencia*. The stone's use has included interior walls and floors, monuments, architectural elements and exterior cladding.

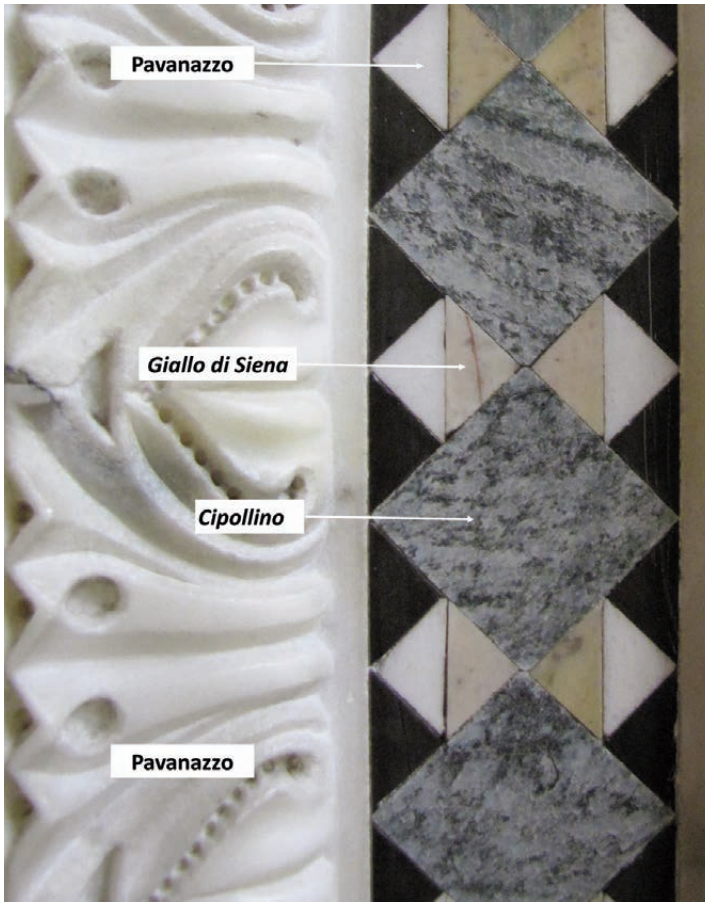
Valencia Marble is a partially metamorphosed Upper Cretaceous limestone from the quarries of Barxeta (also known as Barcheta) and Quatretonda near Valencia in Spain. Quarrying of the stone first took place in Roman times during the reign of the emperor Augustus. Both *Crema Valencia* and Rosa Valencia are fine-grained partially recrystallised limestones. Pressure dissolution has created cross-cutting veins of haematite-rich clay minerals. The yellow and pink colouration is a result of varying quantities of the iron oxides haematite and limonite.

(7) *Cipollino*

This stone has been cut to form small diamond-shaped inserts (Fig. 10) and is most likely to be a *cipollino*, a true geological marble with a distinct large-scale green and white banding, which can only be seen clearly when the stone is used for wall panels or supporting columns. Unfortunately, the striped nature of the stone can barely be distinguished on the small inserts, although with the eye of faith a subtle banding in some pieces of cipollino can be discerned. The marble is named *cipollino* from the resemblance of the stone's foliation to a cut onion (*cipolla*).

In 1882 Farmer and Brindley included in their advertising material the words "sole agents for grand Cipollino marbles".[18] At this date they may be referring to a stone from the Alps known as *Swiss Cipollino* or to a similar stone from reused Roman spolia that had been quarried in Greece. By 1886 the entry had been updated to "sole agents for grand antique Cipollino".[19] Some years later, in, or shortly before, 1898, William Brindley rediscovered the old Greek quarries, the source of the 'antique' variety of *Cipollino*, "after [an] extensive search on the Island of Euboea", when he stated that "the quarries are now being reworked, several shipments of beautiful quality having arrived in London."[20] By 1899 Farmer and Brindley had become quarry proprietors of "Greek Cipollino".[21]

Figure 10 Diamond-shaped Cipollino *inlay (field of view: 50mm ¥ 105mm, east side, north end of tomb).*



In view of the date of the rediscovery of the quarries on Euboea, the inserts in the tomb would need to be derived from spolia to be a Greek Cipollino, known as *Cipollino Verde*. If a spolia source, then the stone came from the southern flanks of Mt Ochi, near Karystos, on the Greek island of Euboea. The island is part of a complex geological story, which includes multiple phases of Cretaceous metamorphism of Permian limestones to form the *Cipollino Verde*. The original carbonate sediments were subjected to high temperatures and high pressures resulting in a range of decoratively attractive deformation structures. Geologically the stone could also be called a carbonate mylonite. The green banding is a result of impurities in the marble, including the green minerals chlorite and epidote. *Cipollino Verde* was first quarried by the Romans who called the stone *Marmor Carystium*. It was exported throughout the Mediterranean region and notably to Rome where more than 500 columns of this marble have been recorded.

If the inlay is not re-used spolia, then the stone is *Swiss Cipollino*, the quarries at Saillon on the Rhone Valley in the upper Alps having been opened sometime around 1873. The marble was successfully marketed as *Grand Cipolin antique* and *Grand Antique de Saillon*. It has been stated that the green ribbon-like laminations are not so uniform or as well defined in the *Swiss Cipollin*o as in the *Cipollino Verde*, and the marble was only 'occasionally' imported into England.[22]

(8) *Spanish Broccatello*

Inlaid as diamonds in the eight corner panels of the tomb (Fig. 11, *opposite*) and as alternating lozenges in the four triangular corner decorations to the *Lapis Lacedaemonius* panels (Fig. 7) is a marble of yellow, claret-red and blue-white hues. This stone is likely to be a *Spanish Broccatello* marble, also known as *Brocatelle d'Espagne*. Broccatello is a reference to its resemblance to brocade (*broccato*) a richly decorated woven fabric with a raised design, often with gold threads.

Spanish Broccatello is an Early Cretaceous limestone quarried near Tortosa in Catalonia, Spain. The marble has been used for monuments, columns and paving since the Roman period and was especially popular during the 18th century for inlay work. The stone is a fossiliferous limestone; tiny pieces of broken shell can be seen as white inclusions in some inserts (Fig. 11). A calcite cement, containing varying quantities of iron oxides, binds the stone's clasts and produces the distinctive colour palette. Watson, records that "instances of its use to form a mosaic pavement may be seen in the chancel of Bristol Cathedral (1895), and in those of Truro (1886) and Peterborough (1892)."[23] The reference to Truro confirms that *Spanish Broccatello* was available and being used for a prestigious ecclesiastical commission at about the same time as the production of Archbishop Tait's tomb. By 1909 a "negligible quantity" of *Spanish Broccatello* was being imported for the British market.[24]

(9) *Giallo di Sienna*

There are a number of small insets of a yellow marble, some lozenges (Fig. 5) and others as half-diamonds (Fig. 10). This is

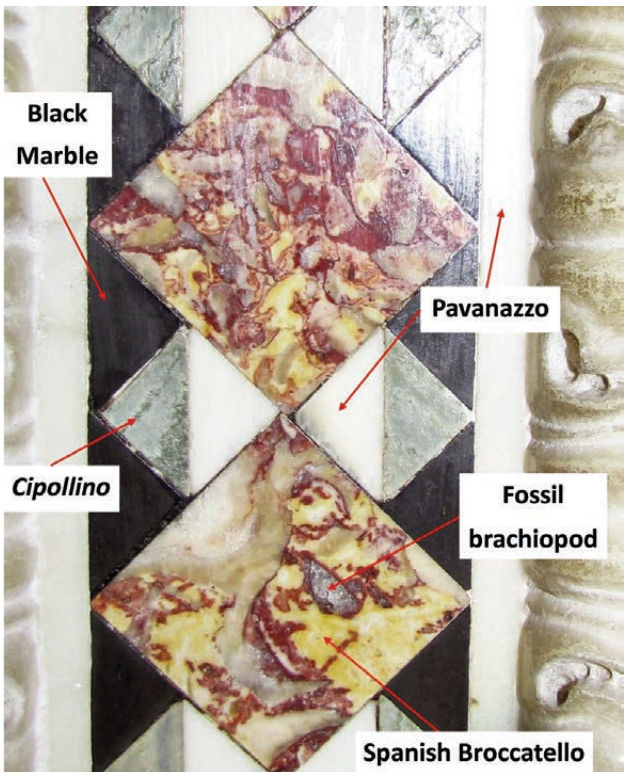


Figure 11 Diamond-shaped Spanish Broccatello *inlay (field of view: 50mm ¥ 75mm, west side, south end of tomb).*

likely to be *Giallo di Siena* a yellow marble from the Province of Siena in the Italian region of Tuscany. There appears to be insufficient red veining to be *Crema Valencia*. The best quality stone is said to have been quarried at Montarrenti, near the town of Sovicille, not far from Sienna.

The colour has been described as an egg-yolk yellow, although *Giallo di Sienna* marbles have a wide colour range and in such small pieces of stone as appears on this tomb there will be some natural variation. The colour is derived from varying quantities of iron minerals present in the form of goethite and limonite. Where the limestone has fractured or been dissolved, a clean white calcite has often been precipitated. Some inserts show serrated lines called stylolites formed by carbonate dissolution and stained violet by iron oxides.

The marble is quarried from the Tuscan Metamorphic Complex, part of the Apennine mountain range. Before being weakly metamorphosed the stone was a fine-grained marine Jurassic limestone. In 1887 (two years after the tomb was constructed) an English stone merchant reported that "the quarries do not seem to have been properly opened up, they are so many scratches on the side of the mountains, and very few large blocks are produced".[25] Quarrying in the region for the yellow marble is said to date back to Roman times and was carried on intermittently, and often on a small scale, until the 21st century saw the opening of large modern quarries. *Giallo di Sienna* has been used for decorative stonework in the cathedrals of Sienna, Orvieto and Florence. In more recent years the marble has had a worldwide distribution.

(10) Verde Antico

A green, fragmentary marble can be seen as inserts in numerous locations around the tomb, e.g. as small lozenges alternating with yellow *Giallo di Siena* adjacent to the *Rosso* marble inscriptions (Fig. 5). This is strictly speaking an ophicalcite breccia; in this instance a serpentinite that contains a good deal of carbonate minerals. In the building trade, serpentinite (or serpentine) is commonly called *Verde Antique*, or *Verde Antico*. In the latter half of the 19th century such stones were quarried throughout Europe for decorative marbles, including in Italy, the French Alps, Greece, Norway, and Great Britain. There are many stones that match the description of these marbles and in the absence of contemporary documentation a provenance can only be tentative.

The term serpentinite comes from the stone's resemblance to a serpent's skin. The rock forms from the metamorphism of magnesium-rich silicate rocks, such as a peridotite. These rocks are recognised as crystallising at considerable depth and once formed part of the oceanic lithosphere. Their presence on continents is associated with obduction, the process whereby rocks are scraped off the descending ocean plate at a convergent plate boundary and thrust onto the adjoining plate, such as occurred during the formation of the European Alps. Metamorphism occurred beneath the ocean when the rock underwent hydrothermal alteration to form secondary hydrous minerals from within the serpentine group (a process called serpentinisation), such as lizardite and chrysotile. A further phase of metamorphism often occurred when the sepentinite became part of a mountain belt. These rocks are often highly fractured (brecciated) resulting in intricate veins of secondary white calcite, having reacted with crustal carbon dioxide released during carbonation reactions from surrounding metasediments. Serpentinites and ophicalcite breccias are complex rocks and often have a complex geological history.

In 1886 William Brindley located the ancient *Verde Antico* quarries in Thessaly, Greece, and from here he supplied marble for Westminster Cathedral. It should also be noted that in 1888 the firm of Farmer and Brindley used a similar-looking serpentinite called *Verde di Prato* at St Paul's Cathedral for the altar screen and the pavement leading to the altar table, and it is therefore possible that William Brindley had supplies of *Verde di Prato* available to him a few years earlier for the Archbishop's tomb. Blagrove, in 1888, stated of *Verde di Prato*, "this is a deep green serpentine with dark spots, occasionally consisting of noble serpentine."[26] The stone of the Archbishop's tomb matches this description. If this is a correct identification then the marble was quarried from near the town of Figline, a few miles from Prato, north-west of Florence. It was quarried in medieval times (many of the striped Tuscan churches make use of *Verde di Prato*) and after a lull in activity quarrying recommenced, more extensively, in 1860. In the absence of a contemporaneous written record, a degree of uncertainty regarding provenance may always exist when dealing with such small inserts. Ruth Siddal suggests, from photographic evidence alone, that the marble used by Brindley on the tomb may be a sheared variety of *Verde Antico*.[27]

(11) *Marmo Pavonazzetto*

There are a number of diamond-shaped pieces of a breccia composed of angular white marble fragments bound in a violet matrix located in two of the side panels of the tomb (Fig. 12, *overleaf*). This is *Marmo Pavonazzetto*, from Iscehisar in the province of Afyon, Turkey. As for the *Pavanazzo*, its name derives from the Italian word for peacock (*pavone*). The marble is known by other names including *Marmor Phrygium*, *Marmor Docimium* and *Marmor Synnadicum*. It is a breccia of varying sizes of white marble clast set in a red-violet-black coloured matrix.

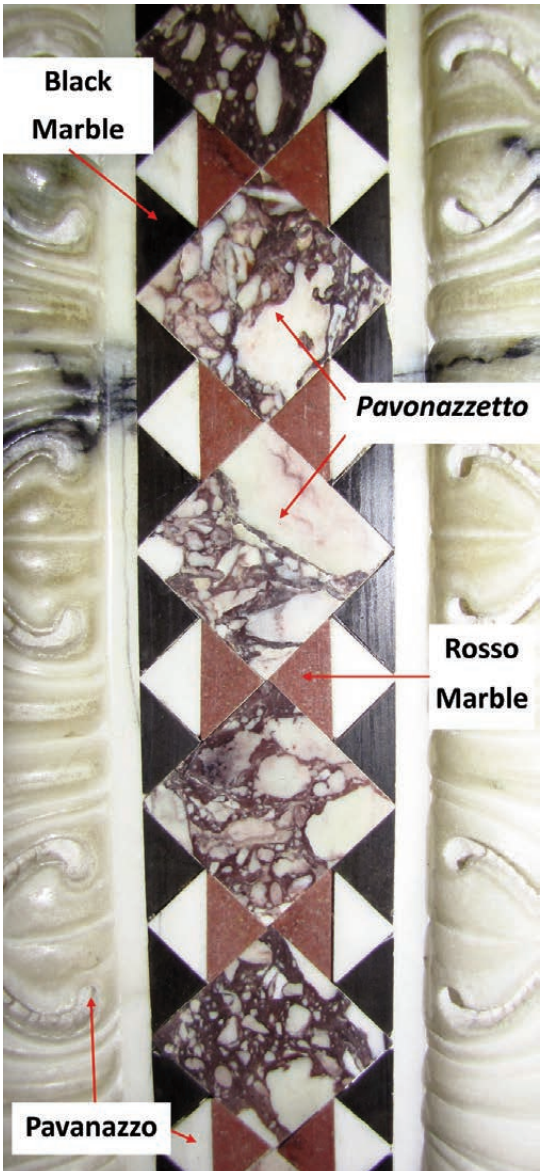


Figure 12 Diamond-shaped Marmo Pavonazzetto *inlay (field of view: 60mm ¥ 180mm, south side, west end of tomb).*

The marble was quarried by the Romans and exported to numerous sites throughout the Mediterranean region. It was highly prized probably because of its purple colouration imbued with the Roman symbolic signification of power and wealth. It was used extensively for architectural features such as columns, wall panels and flooring. An example of two large columns of *Marmo Pavonazzetto* can be seen in the Pantheon in Rome.

In 1885 William Brindley's firm (the tomb's constructors) were described as sole agents for the 'pavonazzetto' stone quarries,[28] the same year in which Archbishop Tait's tomb was unveiled. It is perhaps hardly surprising that they used pieces of this marble for embellishment.

(12) *Pavanazzo* (as inlay)

There are numerous triangular inserts on the monument as well as other architectural embellishments made from a near-white marble (Figs 8 to 12). The provenance of the white marble is difficult to determine from an inspection of the triangular inserts alone. However, the thin white marble bands encircling both the *Rosso* marble panels (Figs 5 and 6) and the *Lapis Lacedaemonius* panels (Fig. 7) clearly show a broad dark banding matching the principal constructional marble of the tomb. This suggests that the pure white triangular inlays are also selected pieces of Pavanazzo (*see* stone (2) above).

(13) *Black Marble*

Black marbles are notoriously difficult to identify, especially so from such small inserts. The stone could be Belgian Black Marble, a carbonaceous limestone of Devonian-Carboniferous age often referred to as Tournai Marble. As an alternative, Derbyshire Black Marbles were frequently used in England as architectural elements and in domestic inlay work. There are also similar marbles available during the late 19th century from Kilkenny and Galway known collectively as Irish Black Marbles. All of these sources would have been known to William Brindley at the time of the tomb's manufacture.

The cenotaph of Archbishop Tait is a splendid example of Victorian Gothic (Fig. 13, *oppoosite*, and Fig. 1). It exemplifies the ideals of the Gothic revival of the second half of the 19th century, from the recumbent effigy to the archetypal rectangular tomb chest, while conveying a commission of great import executed to the highest standards available. Numerous medieval antecedents can be seen today in Canterbury Cathedral's choir and Trinity Chapel, where painted surfaces and newly polished domestic stones once provided a medieval visual extravagance. Archbishop Tait's monument still recreates this impact upon the viewer, not only by the employment of high quality craftsmanship, but through the use of a wide range of exotic Mediterranean marbles, some of which were newly available to the decorative stone market of late Victorian Britain.

Acknowledgements

My thanks go to the following: Di Clements and Charles Hugkulstone for their helpful comments on early drafts; to Dr Ruth Siddal for her comments on an early draft of this article, for her general observations on the marbles cited and for the identification of the *Lapis Lacedaemonius* and *Pavonazzetto* marbles; to Matt Riley of the Sedgewick Museum; and to the staff of the Cathedral Archives at Canterbury Cathedral.

Notes

[1] *The Builder* (02/06/1883), Vol. 44, January–June 1883, 740

[2] Canterbury Cathedral *Chapter Act Book* 1884, Fo. 477, 490, 494; *Chapter Act Book* 1885, Fo. 9, 10, 13

[3] *Canterbury Diocesan Gazette* **5** (1896–7), 247

[4] *The Builder* (24/05/1885), Vol. 49, July–December 1885, 563

[5] The website of the Victoria and Albert Museum: http://collections.vam.ac.uk/item/O349503/folded-hands-of-archibald-campbell-hand-boehm-joseph-edgar/ [accessed 07/08/2019]

[6] *The Builder* (24/05/1886), Vol. 50, January–June 1886, 605

[7] *Post Office London Directory (POLD)*, (see 'Part 2: Commercial & Professional Directory' and 'Part 3: Trades & Professional Directory')

[8] MS: letter from H. A. Miers to W. Brindley, 29 November 1899. Corsi file. Mineralogical Collections archive OUMNH. Cited by Cooke, Lisa 2010 'The 19th century Corsi collection of decorative stones: a resource for the 21st century?', *in* Přikryl, Richard, and Török, Ákos (eds) *Natural Stone Resources for Historical Monuments*, Geol Soc Spec Publ **333**, 191

[9] William Brindley's Obituary, *Quart J Geol Soc* **76**, 1920

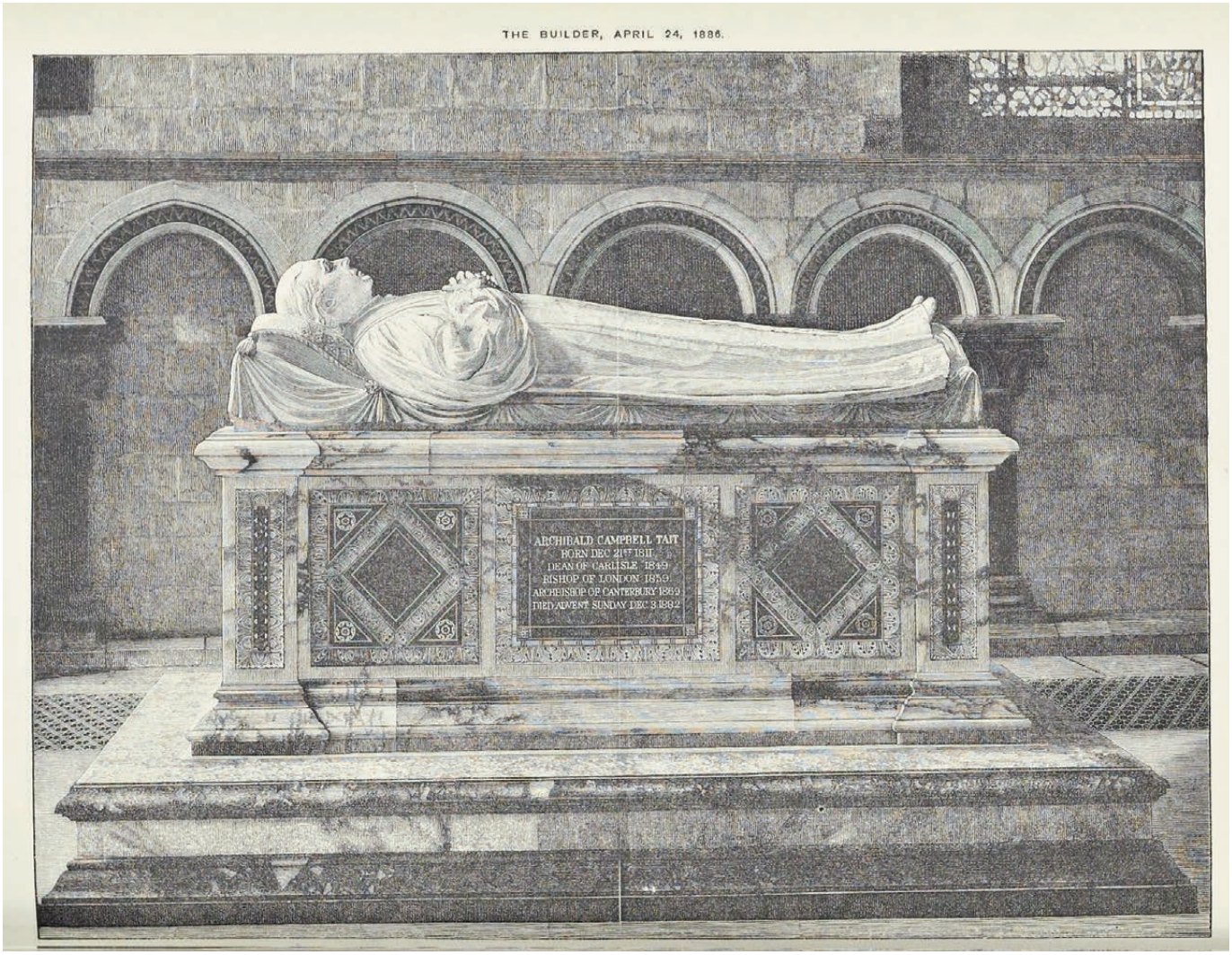

THE BUILDER, APRIL 24, 1886.
ARCHIBALD CAMPBELL TAIT
BORN DEC 21ST 1811,
DEAN OF CARLISLE 1849
BISHOP OF LONDON 1856
ARCHBISHOP OF CANTERBURY 1869
DIED ADVENT SUNDAY DEC 3 1882

Figure 13 Engraving of Archbishop Tait's monument by James Davis Cooper executed from photographs assisted by the drawings of the architect, John Oldrid Scott. Cooper was an engraver of books and a notable wood engraver and draftsman. His workshop was located in the Strand, London (source of image: The Builder *for 24 April 1886.)*

[10] *Mapping the Practice and Profession of Sculpture in Britain & Ireland 1851–1951*:https://sculpture.gla.ac.uk/view/organization.php?id=msib1_ 1246101417 [accessed 07/08/2019]

[11] Stocker, Mark Andrew 1986 'The Life and work of Sir Joseph Edgar Boehm', unpubl. PhD Thesis U Hull, 185–6; Collinson, Patrick, Ramsey, Nigel, and Sparks, Margaret (eds) 1995 *A History of Canterbury Cathedral*, Oxford UP, 541

[12] The Builder (24/05/1886), Vol. 50, January–June 1886, 605

[13] *Marble and Marble Working* (Renwick 1909)

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[16] Koutsovitis, P. *et al.* (eds) 2016 'Mineralogical, petrographical and geochemical features of the unique Lapis Lacedaemonius (Krokeatis Lithos) from Laconia, Greece: approach on petrogenetic processes within the Triassic volcanic context', *Bull Geol Soc Greece* **50**

[17] Dr Ruth Siddall, U College London, pers. comm. 02/05/2019

[18] *Post Office London Directory (POLD) 1882*, Part 2: Commercial & Professional Directory

[19] *Post Office London Directory (POLD)* 1886, Part 2: Commercial & Professional Directory

[20] Brindley, W. (F. G. S.) 1899 'The Ancient Marble Quarries of Greek Cipollino', *J Roy Inst Brit Archit* **VI** (ser. 3) November 1898–October 1899, 43–4

[21] *Westminster Cathedral: From Darkness to Light* (Rogers 2003, 49)

[22] British and Foreign Marbles and Other Ornamental Stones (Watson 1916, 235)

[23] *British and Foreign Marbles and Other Ornamental Stones* (Watson 1916, 228)

[24] *Marble and Marble Working* (Renwick 1909, 91)

[25] *Decorative Stone: the Complete Sourcebook* (Price 2007, 92)

[26] *Marble Decoration and the Terminology of British and Foreign Marbles: a Handbook for Students* (Blagrove 1888, 116)

[27] Dr Ruth Siddall, University College London, pers. comm. 21/05/2019

[28] *Post Office London Directory (POLD*) 1886, Part 2: Commercial & Professional Directory

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UCL Earth Sciences Decorative Stone Collection: https://www.ucl.ac.uk/~ucfbrxs/Homepage/UCLDecorativeStone/UCLBuildingStones.htm [accessed 07/08/2019]

Urban Geology, a series of urban walks compiled by Dr Ruth Siddall: https://www.ucl.ac.uk/~ucfbrxs/Homepage/UrbanGeology.htm [accessed 07/08/2019]The John Watson

Collection in the Sedgwick Museum of Earth Sciences (Geology Common Room), Cambridge

The publications and websites of various commercial marble and stone retailing companies.

Some aspects of the structural geology around Almograve, Algarve region, south-west Portugal

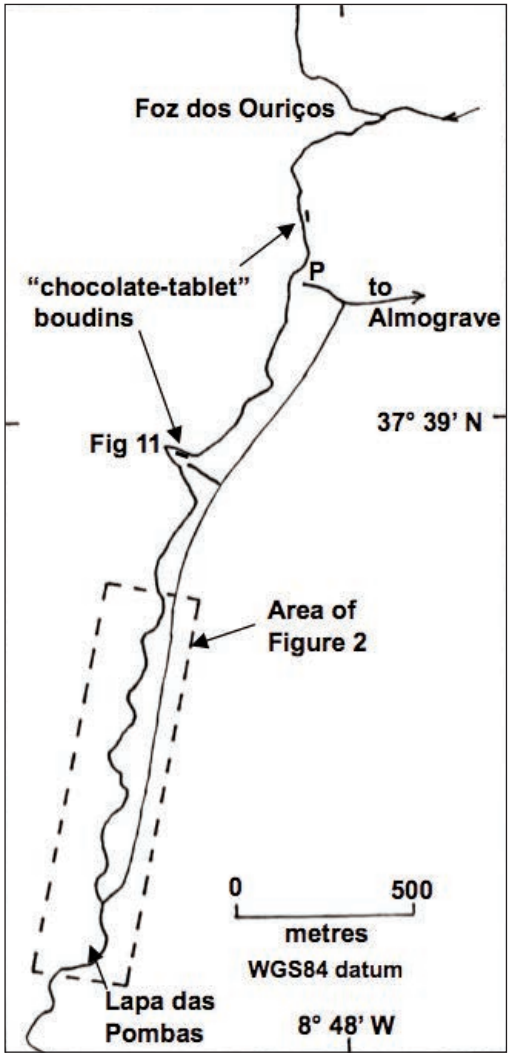
Duncan Woodcock

1 Introduction

Carboniferous turbidites in coastal exposures around Almograve show a wide range of deformation features that resulted from compression within a foreland fold and thrust belt during the Variscan Orogeny (Park 2014). This article attempts to display some of these features, principally by means of a series of photographs with explanatory captions.

Figure 1 provides a sketch overview map of the area. The large car park at Almograve beach ('P' on the map) provides a convenient starting point. An unsurfaced road runs south to the small fishing port of Lapa das Pombas, while a coastal path runs north to the beach at Foz dos Ouriços. In this article I concentrate on two areas of particular interest: the northern side of Foz dos Ouriços and a length of coast extending northwards from Lapa das Pombas for about half a kilometre.

Figure 1 (below) Overview sketch map of the area around Almograve.



2 Coastal section north of of Lapa das Pombas

This section displays a variety of fold types, in various orientations, both in the cliffs and on wave-cut platforms during times of low tide. There is access right along the top of the cliff and, in places, down to sea level. Figure 2 is a sketch map of the section, showing a number of locations of particular interest, many of which are displayed in Figures 3 to 11 on pages 104–6.

Figure 2 (right) Detailed sketch map of the coastal section north of of Lapa das Pombas.

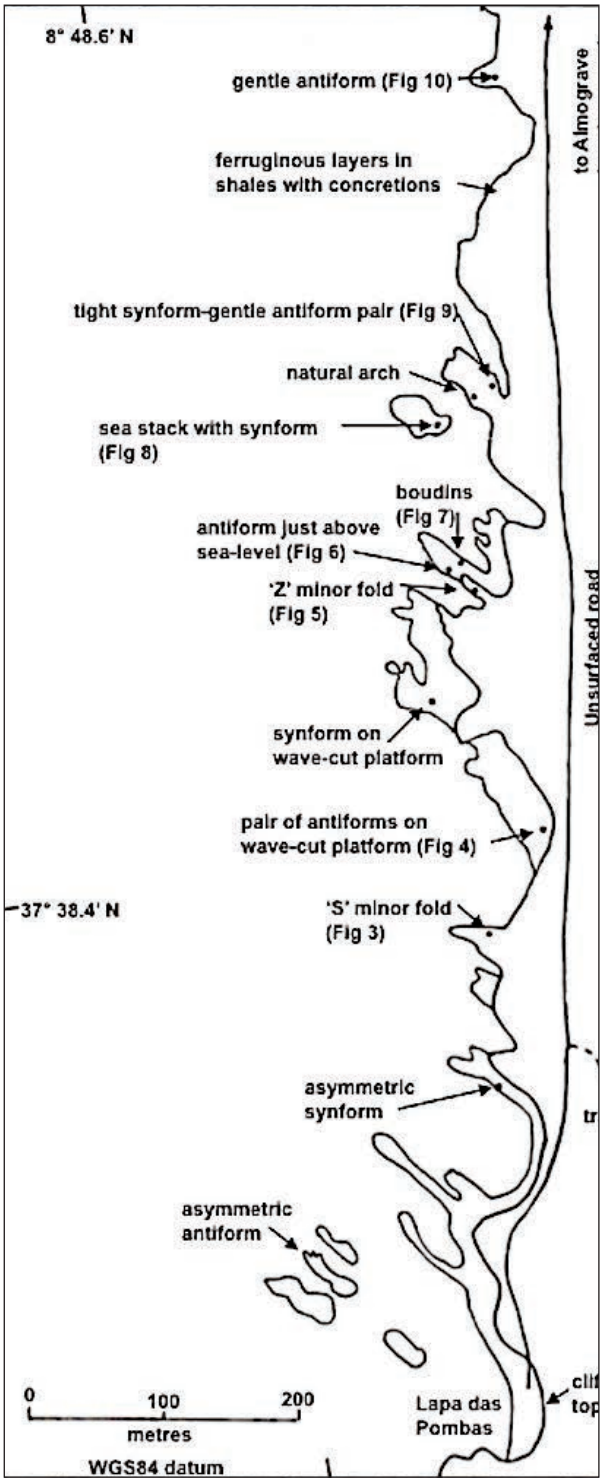


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Figure 3 A minor 'S' fold that developed on the left limb of a larger synform, which contains two thick sandstone beds in the left of the photo (view to 330° [magnetic], down the gentle plunge of the minor fold; height of minor fold c. *5m).*

Figure 4 (right) A pair of antiforms exposed in the modern wave-cut platform (view to c. *320°, down the plunge of the intermediate synform — not obvious in photo; width of view* c. *15m at the south end ofthe photo).*

Figure 5 A minor 'Z' fold that developed on the vertical right limb of a larger synform, which contains a thick (1–2m) sandstone bed that defines a narrow promontory immediately to the right of the cliff face (view to N, slightly oblique to the minor fold, which plunges towards 330°; height of cliff c. *15m).*

Figure 6 Oblique view (to N) of an antiform that plunges towards 320° (height c. 3–4m).

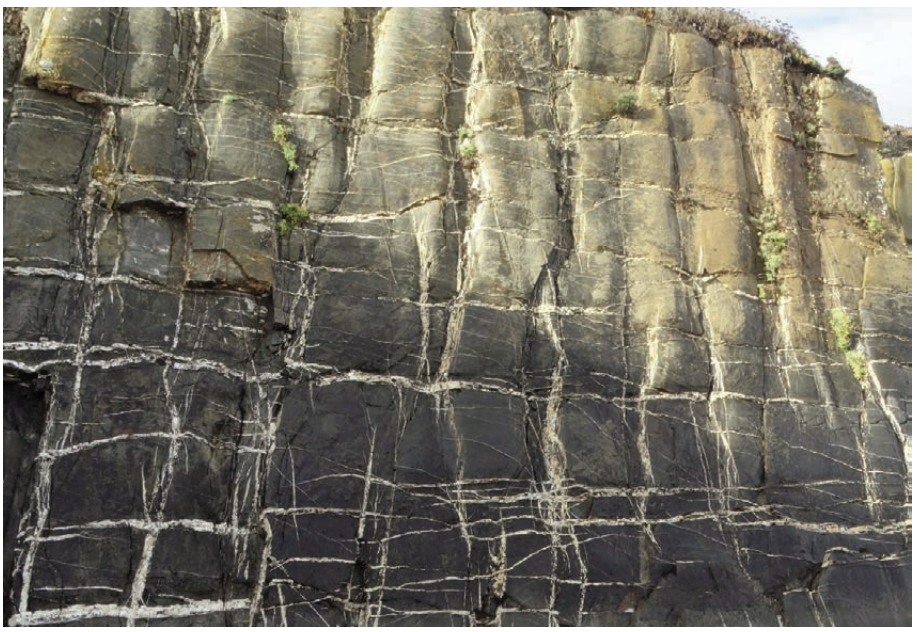
Figure 7 Subvertical boudins displayed on the north side of the narrow promontory (Fig. 5) — view to 240°. These boudins developed as a result of sideways stretching of the thick competent sandstone bed that makes up the promontory. The resulting 'pinch and swell' of the bed can be seen as a subvertical lineation in the figure. The promontory is too narrow to allow a bed-parallel view of the boudins; equivalent views can be examined at Foz dos Ouriços (Figs 17 and 19).

Figure 8 Open synform developed in a sea-stack immediately offshore (view to 310°, slightly oblique to the plunge of the fold — towards 340°; for scale, note pair of seagulls on top of stack).

Figure 9 A tight synform — gentle antiform pair of folds that plunge towards 340° (height of cliff c. *20m).*

Figure 10 A gentle antiform defined by three thick sandstone beds (view to 340°, along the plunge of the fold; height of cliff c. *10m).*

Figure 11 View to 200° of a 10m high exposure that displays 'chocolate-tablet' boudinage (see Fig. 1 for location). The pinched necks of the prominent set of vertical boudins contain quartz veins that have infilled tensional cracks produced during extension. A horizontal set of quartz veins, which in general are younger than the vertical set, is the result of a later stage of boudinage (Zulauf et al. *2011).*



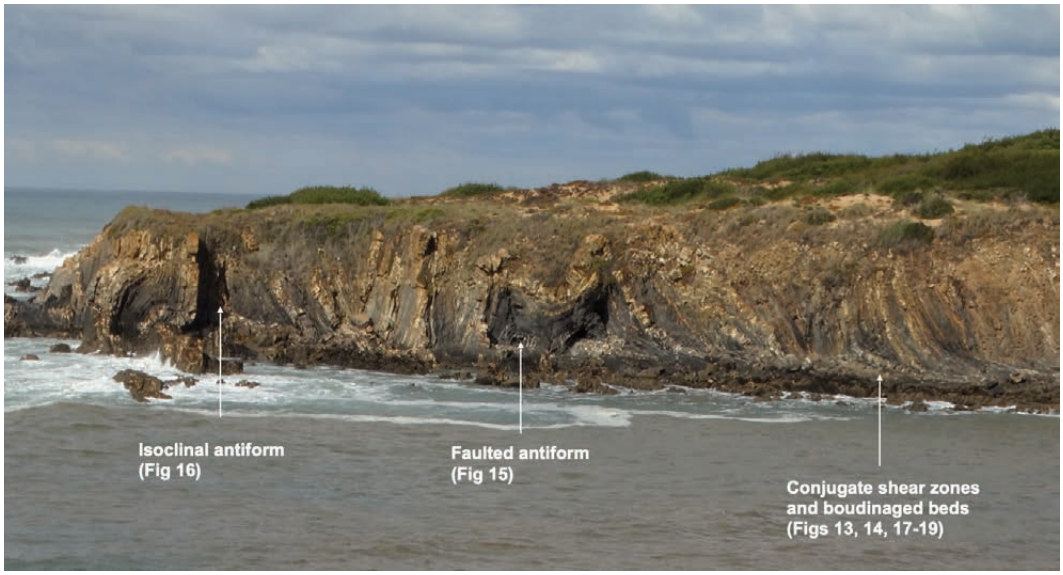


Figure 12 Overview of the northern area at Foz dos Ouriços, annotated to show the location of selected features of interest. The cliffs are 5–10m high, with the whole section c. *100m long.*

3 Northern side of Foz dos Ouriços

The structural geology of the exposures at Foz dos Ouriços has been studied in detail by Dias *et al.* (2017). Many of the locations that they describe are at the southern end on the beach; this has a tidal cut-off that limited access to around low tide when I visited. In contrast, the northern end of the beach can be accessed at most states of tide, although some parts were inaccessible around high tide. Figure 12 comprises a view of this northern area, which has been annotated to show the location of selected features of interest that can be studied in detail; many of these are displayed in Figures 13 to 19 on pages 107–109

Figure 13 (above) Conjugate shear zones containing en-echelon quartz veins (Hancock et al. *1982). These have developed within steeply dipping beds that are exposed on the wave-cut platform on the north side of Soz dos Ouriços (see Fig. 12 for location). The quartz veins infilled tensional cracks that developed during deformation. The lower en-echelon set, which trends to 070°, indicates dextral shear, while the upper set, which trends to 096°, indicates sinistral shear. Taken together, the conjugate pair indicates a direction for the maximum compressive stress towards 083°, consistent with fold axes in the locality, which plunge towards the NNW (horizontal field of view is 1.5m).*

Figure 14 Close-up view of part of the upper set of en-echelon quartz veins. The veins are slightly sigmoidal, consistent with progressive development within a sinistral shear zone.

Figure 15 Antiform, faulted along the axial plane with downthrow to the east (view to 335°, slightly oblique to the plunge of the antiform). Crest of antiform is 2m above the shingle beach. The 'core' of the antiform is exposed again immediately to the south and is visible in the lower right-hand side of the figure; it plunges at 12° to 335°.

Figure 16 Isoclinal antiform, defined by a thick sandstone bed, with a shale core that shows a strong vertical cleavage (view to 330°, along the plunge of the fold).

Figure 17 Boudinage developed in two thick (0.3–0.5m) sandstone beds. Note the intense quartz veining in the boudin necks and the 'out-of-phase' relationship between the two sets that produces a 'snug fit'.

4 The wider area

The Almograve area lies within the Parque Natural do Sudoeste Alentejano e Costa Vicentina (PNSACV) and is part way along the Rota Vicentina, a long-distance coastal path that runs north from Cape St Vincent for 230km to Santiago do Cacem (Rota Vicentina website). From Lapa das Pombas, the coastal path runs south through an area of sand dunes and provides several spectacular coastal views. In this area the deformed Carboniferous rocks are overlain unconformably by subhorizontal Cenozoic sandstones, as can be seen in Figures 20 and 21, *overleaf*.

Fortunata and Costa (2009) provide details of several locations within PNSACV. The unconformity at Telheiro, where folded Paleozoic rocks are unconformably overlain by subhorizontal Mesozoic sediments, is particularly recommended.

*Figure 18 The conjugate pair of shear zones containing en-echelon quartz veins on the left-hand side of the figure developed during the deformation of the thick (*c. *1m) sandstone bed. The orientation of the shear zones and the sense of shear is the same as the shear zones in Figure 13. The sense of shear here indicates a direction of compressive stress that is orthogonal to the thinner sandstone bed in the right-hand side of the figure that shows boudinage.*

Figure 19 A closer view of the boudinaged bed in Figure 18. Note the quartz veining in the boudin necks and the deformation of the thin shale bands around the boudins. A small fault on the right-hand side displaces the boudinaged bed.

Figure 20 At this location, vertically dipping sandstone beds have been planed off at c. *25m above sea level and unconformably overlain by subhorizontal Cenozoic ferruginous sandstones. (view to 340° from cliff top at 37° 37.63' N, 8° 48.59' W, south of Lapa das Pombas. The vertical beds appear to be separated from lower beds dipping steeply to the right by a faulted zone.*

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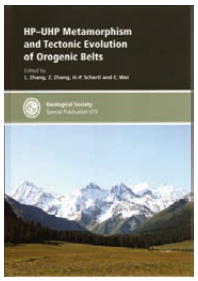
Figure 21 A close-up view of the faulted zone in Figure 20. The zone comprises four faults with intervening slivers of rock.

Book review



Zhang, L., Zhang Z., Schertl, H.-P., and Wei, C. (eds) 2019 *HP–UHP Metamorphism and Tectonic Evolution of the Orogenic Belts*. London: Geological Society Special Publication 474 (ISBN 978-1-78620-399-1; 362pp; hardback £125)

This book is a special issue compiling most of the lectures presented at the 'HP–UHP* metamorphism and tectonic evolution of orogenic belts' session. It was held at the 35th International Geological Congress, Cape Town, South Africa during the summer of 2016.

The report begins with an introduction paper on HP–UHP metamorphism and tectonic evolution of orogenic belts, presenting the 15 papers that follow. These papers are grouped into three parts, each of these sections focusing on different aspects, such as new developments in the determination of metamorphic P–T conditions and their timing, an overview of four well-known HP–UHP metamorphic belts and, finally, research for several newly discovered or not so well understood HP–UHP belts, with a focus on their geochronology and geochemistry.

The first part is probably the most challenging for an amateur geologist, as it presents new and less known techniques to study metamorphic timings and P–T conditions in eclogites and metabasites, using garnets and zircons. This part is richly illustrated with thin sections, compositional maps, garnet profiles, cation variation plots, phase modelling through P–T stability phase diagrams, ACF diagrams, isochron plots, HREE/REE patterns, thermodynamic datasets and MORB composition techniques. It also introduces and contrasts methods in chemical observations, mass spectrometry and the pros and cons of garnet Lu–Hf and Sm–Nd geochronology and Ti-in-zircon thermometry.

The second part is very accessible to anyone with basic knowledge in metamorphism, with sketch maps and schematic diagrams of the lithosphere and the asthenosphere in the subduction and orogen zones presented— the Dabie-Sulu belt (east–central China), the Tianshan belt (Himalaya), the North Qaidan belt (north-west China), the Himalayan orogen and the Sumdo Complex (Tibet).

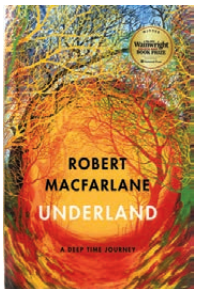
The third part is rather interesting, focused on case studies in less known belts through analyses of rock suites and even archaeological artefacts. These studies include eclogites from the Marun–Keu complex in the Polar Urals (Russia), analyses of eclogites in North Qaidan belt (north-west China), data of Oligocene granitoids in the eastern Gangdese arc, data from gneiss samples in the Dabie eclogite-bearing terrain (east–central China) and a geochronology case study of HP metamorphic paragneisses from the Eastern Himalayan Syntaxis. In this part, there is a particularly enjoyable paper on the analysis of jadeitite jade objects excavated in the Dominican Republic. Archaeological jadeitite artefacts have helped expand the understanding of plate tectonics and HP-UHP metamorphism in subduction and collision zones as well as providing information about precolonial civilisations. This paper reveals that newly discovered jadeitite sources in Cuba and the Dominican Republic have highlighted the interactions and complex network of exchange between indigenous cultures throughout the Caribbean islands. Before this discovery, Guatemala was the only known source of Mesoamerican jadeitite. The study is completed with petrography, mineral chemistry and bulk-geochemistry analyses of the artefacts that define their provenance.

Though heavy-going reading at times, this London Geological Society Special Publication is an interesting read for those who enjoy metamorphic geology, and serves as a nice refresher for the concepts learned in the OU modules, as well as teaching new developments that are being used for geochronology and geochemistry studies.

* high-pressure, ultra-high-pressure metamorphism

— Isabel O'Brien, BSc (Hons) Natural Sciences (Earth Science)

Book review



Macfarlane, Robert 2019 *Underland: a Deep Time Journey*. London: Hamish Hamilton/ Penguin Books (ISBN 978-0-241-14380-3; viii + 488pp; hardback £20)

This is an interesting book with themes on several levels wrapped around its one-word main title. It is a book with a central message about the Earth's environment, and also, like Macfarlane's previous books, a personal journey.

Macfarlane uses the term 'underland' both literally and metaphorically. In his explorations underground, through a series of natural and man-made cavities, he examines geology, physical geography, human history, exploitation of the Earth, and personal challenges, including very personal thoughts and fears. Some of his intimacy with the reader, although honest and natural, may not be comfortable to some readers.

Most of the physical 'underland' that Macfarlane explores and describes is literally deep underground: caverns, caves, moulins in glaciers, and man-made mines and silos. He also includes a chapter on the 'understory', using Epping Forest as its focus. Rather than geology, this chapter is about ecology, about the understorey of the soil and plant interconnections below the surface.

Macfarlane begins his descent with a general discussion of underground hollows around the world, and with a sampling of underground stories throughout human history, beginning with the Sumerian Epic of Gilgamesh. This sets the tone of the book: that it will include both literal 'underground' and 'underland', and metaphorical, downright philosophical underlands of personal and human-shaping ideas. In two telling sentences in his introductory chapter he leaves no doubt about this multipurpose intent: "*Underland* is a story of journeys into darkness, and of descents made in search of knowledge." and "For more than fifteen years now I have been writing about the relationships between landscape and the human heart."

Do not let this 'put you off', thinking that this is 'just' another book about how we are ruining our planet. There is solid scholarship, as always, behind all of Macfarlane's descriptions and discussions, leaving no doubt about his wide reading and diligence to anchor his statements and opinions in fact. It is a long book — 425 pages, plus 20 pages of notes, 18 pages of bibliography, and a 20-page index.

The places Macfarlane explores include the Somerset Mendips; Yorkshire's Boulby mines; the aforementioned Epping Forest understory; the underground cavities beneath Paris; the caves and underground rivers of Italy's Carso; the caves of Slovenia's Highlands; the prehistorically inhabited, almost inaccessible, caves of Lofoten in Norway; exploration for new underground sources of oil offshore at Andøya, Norway; glaciers, moulins and under-glacier meltwaters in eastern Greenland; and Finland's silo 'hiding place' for spent nuclear reactor rods in Olkiluoto.

At each of these places he also describes and compares them to similar other places in the world.

He finally 'emerges' from underland at Nine Wells Wood near his home in Trumpington, near Cambridge. He visits it with his four-year-old son, where he tries to explain to him how the spring waters emerge as if by 'magic' from underground.

At each place's underland Macfarlane gives a combination of geographical-geological and human history. In the Mendips there are caves to explore and also Neolithic and Bronze Age burials; at Boulby, there was originally mineral extraction and now exploration in its flooded mines for the universe's 'dark matter'; in Epping Forest's, and all the world's, understorey — the soil — there is a wealth of new Earth science knowledge being discovered; Parisians mined the Eocene Lutetian limestone beneath them originally for building stone, then later used these man-made caverns as catacombs to solve their human burial problems, and now for some singular forms of personal 'recreation'; in the karst and hollow lands of Carso, Italy and of the Slovenian Highland caves he presents interesting geology, the exploration of underground rivers, and descriptions of their use in horrible, tragic human wars and suffering; the prehistoric paintings in nearly inaccessible caves at Lofoten, Norway reveal — or not — unfathomable aspects of human thought, protected and preserved by the solid metamorphic geology of the region; the renowned social equity and well-being of Norway, encompassing both modern and traditional ways of life, is threatened by conflict over further off-shore exploration for oil resources to maintain this wealth as the output of Norway's current North sea wells peak and diminish; a similarly themed discussion underlies Macfarlane's explorations of the 'pristine' landscape of eastern Greenland's glaciers around Kulusuk and the Knud Rasmussen Glacier, as well as the science of ice cores and what these show us about deep-time Earth climate history; and in using the example of Finland's man-made hiding place at Olkiluoto Macfarlane discusses the use of the geology and the human endeavour to seal 'forever' the dangerous nuclear waste we have created in our need for energy, to resolve the problem we have created for generations thousands of years into the future.

The meaning of a book — the impressions and messages you take from it as you read it — will always change, repeatedly, throughout your reading, until you reach the last page. In his explorations of these various underlands Macfarlane probes the concept of 'Deep Time' — past and future — through geology, landscape and human history. Throughout the book he returns to and discusses the concept of the Anthropocene, exploring geologists' struggle to define and date the creation of a new geologic period. In — perhaps — typical Macfarlane fashion, in one of his final discussions of the Arthropocene, he becomes lyrical. "The idea of the Anthropocene repeatedly strikes us dumb." He turns to the 'cultural theorist' Sianne Ngai's idea of 'thick speech' — confusion, struggle to express, futility to even try: "I had an Anthropocene ox on my Holocene tongue."

While not wishing to diminish my like of this book and its ideas, both geological and philosophical, I would be presenting an incomplete review if I did not express my opinion that I think the book is sometimes overwritten. Robert Macfarlane writes fluently and beautifully, expressing complex ideas intermixed with his own feelings and opinions. But I often felt there was no need to be so frequently telling the reader in detail the character of the people he stayed with and in describing every small detail of the insects and foliage, the weather patterns, clouds, sunsets, and other such literary and lyrical passages. And in contrast, one small passage leapt out, for me, as a missed opportunity to emphasise more forcefully an ironic contrast.

Macfarlane describes the beauty of the glacial landscape of eastern Greenland, together with the effect of climate change

on the Greenland ice cap that is changing it — the retreat of glaciers and their more frequent calving of icebergs, less and less annual snowfall and sea ice, and the effect on traditional ways of life. Then he comes to a cliff overlooking a small bay — significantly out of sight of the village of Kulusuk, where he is staying. He dumps on the reader only a brief paragraph, with no further comment on what seem to me to be an obvious contradictory irony, germane to the Anthropocene theme of his book:

"The little bay beneath me is the village's rubbish tip. Thousands of bin bags, a slew of plastic crates, cracked kayaks, melamine cupboards, and white fridges have been heaved over the cliff edge here to make the midden. It looks, in the dusk, like a tongue of ice flow down towards the waterline: a glacier in advance, not retreat."

This is a powerful image, superlatively expressed. But look who is polluting whose environment!

Addendum

Just as I finished reading *Underland* an article by scientific journalist Annie Sneed was published in *Scientific American*'s online blog site, entitled 'Forever chemicals are building up in the Arctic—and likely world wide' (June 12, 2020). It appears that the chemicals now used to replace the ozone-destroying chlorofluorocarbons (CFCs) rise into the atmosphere, react with other chemicals, and form short-chain perfluoroalkyl carboxylic acids (scPFCAs). Arctic ice cores representing at least 50 years duration record scPFCA build-up in our environment, and show that they rain down to Earth, into the underland, *everywhere* and do not go away: "They are characterized by carbon-fluorine bonds, which are the strongest single bonds that can be formed. The bonds are so strong that there aren't really any environmental processes that can break them down." We do not know yet if they are toxic.

— David M. Jones, OUGS Proceedings Editor

Book review

Bond, C. E., and Lebit, H. D. (eds) 2020 *Folding and Fracturing of Rocks: 50 Years of Research since the Seminal Text Book of J. G. Ramsay.* London: Geological Society Special Publication 487 (ISBN 978-1-78620-429-5; 352pp; hardback £100)

Most of you will be familiar with the format of the London Geological Society's Special Publication series. Each volume brings together a series of scientific papers on a given theme, editing and organising them into an attractive, hardback book. This publication is number 487, attesting to the longevity of the concept.

In this case, the theme is the influence of John Ramsay's textbook on structural geology, *Folding and Fracturing of Rocks*, and how the field has developed over the years since its publication in 1967. This was one of the first textbooks to treat structural geology in a rigorous, mathematical manner, bringing together existing methods and developing new techniques that could be used for the quantitative investigation of geological structures.

The Special Publication begins with an introduction that presents the various papers that comprise the volume. This introduction paper is Open Access, so is a worthwhile read if you want to get a feel for the contents of the book. It also provides a brief biography of John Ramsay himself. The papers are grouped into a number of categories, which develop the themes present in Ramsay's book, and help to show the common thread that links the papers together.

The first two of the 17 papers in the book look at the influence of Ramsay's textbook. The first is a personal account of how it affected the lives of two structural geologists, whose choice of career was influenced by the book during their university studies shortly after its publication. They certainly made it sound like an exciting read. I must confess that I was not familiar with Ramsay's work, and I felt inspired enough to seek out a copy to get a feeling for the character of the work for myself. This turned out to be rather more difficult than I had envisaged, but soon a copy was winging its way over from Germany, courtesy of an internet auction site.

The second paper tries to quantify how Ramsay's themes have influenced research in structural geology over the past 50 years. The authors use a number of metrics — citation counts, and the correlation between the growth of papers on given topics and the timing of the book's release, for example — to show how Ramsay's original work, along with a follow-up book with Martin Huber in 1987, do seem to have provided the seed from which a huge body of work has grown. Most impressive is how the literature of structural geology has grown, with numbers of publications barely scraping double digits per year until about 1990, but rising to about 1,200 papers annually today. The paper also breaks down the results to show which of Ramsay's techniques have been the most influential. The impact of the book seems convincing, both in popularising the methods of previous researchers, and in developing new ideas.

We then get into the real 'meat' of the book itself. At this point I have to declare that, on the whole, I am not qualified to make any sound assessment of the validity of the papers themselves. I am not a structural geology researcher, and all the papers here have been subject to the peer-review process. But that does not mean that there is not plenty that an OU geology graduate can take from the papers.

Rather than discuss each paper in turn, I will bring out a few of the threads (as I saw them) that run through the papers, and highlight a few of the papers that brought me particular insight.

One of the major themes in the first few papers is that of progressive deformation, and the ease of confusing its effects with that of multiple phases of deformation. I find this a particular eye-opener, and indeed found it so when I reviewed Haakon Fossen's *Structural Geology* in 2016. In brief, while any rock is being deformed, it will progress through fields of both compression and extension, meaning that, for example, a quartz vein might be folded, then stretched out and boudinaged, all within one deformation event. This can lead to deceptive kinematic markers, such as vergence that may point the 'wrong-way', meaning care must be taken when interpreting minor structures in the field.

Another early theme is that of fold and fault nucleation. Why does a fold form where it does? While the expected fold wavelength is known to relate to bed thickness and competence, how does the early fold nucleation affect this in practice? What is the relation between folds and faults? How important are buckle folds in the real world, or should we be interpreting all folds in the context of associated faulting?

An interesting paper in this regard looks at a superbly exposed fault/fold at Broadhaven in South Wales. Here the authors revisit this classic locality and reinterpret the structure with improved measurement and digitisation, enabling them to identify a complex deformation history belying the apparently simple large-scale fault-propagation fold. It is this outcrop that adorns the cover of the book, echoing the cover of one of the editions of Ramsay's original work.

Another interesting paper looks at soft sediment deformation around the Dead Sea. This again strikes notes of caution for field geologists: the small-scale structures developed during progressive slumping look surprisingly like multiple deformation events in hard rocks. An interesting insight is that sediment roles can be reversed: where a lithified rock would have a competent sandstone and plastic mudstone, soft sediments can have incompetent sands and stiffer muds, owing to the effects of pore pressure and cohesion.

There is plenty among these papers to challenge what you think you know. One such debate is the formation of cleavage refraction, and the timing of cleavage formation relative to folding. Surprisingly, it seems the jury is still out on some of these issues. But it was nice to see how cleavage refraction can be used to quantify the viscosity contrast between the lithological units in a fold.

Continuing the theme of quantifying deformation, there is a useful review paper looking at the techniques used by Ramsay and how the science has progressed since then. The problem comes down to how to work out how a body's shape has changed if you don't know its original shape. You've got to assume *something*, and the assumption made will obviously have an effect on your results. Surprisingly, it seems that the techniques themselves have not developed radically since Ramsay's day; what has advanced is the ability to automate, enabling less labour-intensive analysis and providing better statistics. It is only to be expected that such automation will continue apace with the advances in computational power and machine learning.

From these small-scale structures, we move on to regional tectonics, with three papers looking at the thrust belt in Montana. I particularly enjoyed the first of these papers, which linked nicely with my first degree in physics. Here, the authors measure the magnetic susceptibility of rocks in regions where a clear fabric is not developed. The magnetic susceptibility has a directional dependence and so the response can be plotted as an ellipsoid, which may reflect the deformation the rock has undergone and therefore show a fabric. Unfortunately, the orientation of the ellipsoid is less clear — depending on the mineral involved, we would expect the orientation to change differently under deformation. But what surprised me was how effective this technique was, identifying a fabric in the rocks where none was visible — even if the interpretation needs careful consideration.

Talk of fault reactivation and inversion is a commonplace in the British Isles, which has such a rich tectonic history. But what happens when the extensional faults find themselves in a compressional regime oblique to their original orientation? This is investigated using analogue models in the laboratory, creating normal faults in sand and compressing them again in different directions. There is plenty of data to pore over here, and the results seem realistic enough, but I did wonder how we can be sure that the materials used scale well to the real world.

Extensional versus compressional faults are further explored by using Argon isotope ratios to deduce a temperature-time path for rocks in the footwall of major lineament in the Aegean. Perhaps by this point it should no longer be a surprise that it can be difficult to distinguish an extensional detachment from a thrust by kinematic indicators alone. However, the thermal history shows us how the rocks were heated or cooled and therefore whether they were exposed to cooler, shallower rocks in the hanging wall during extension, or if they were heated by deeper, warmer rocks during thrusting. For a non-specialist, the details here were hard to understand, but it was nice to see discussion of the concepts of closure temperatures and diffusion, which were familiar from third-level OU courses, and to get a glimpse into the highly technical nature of the work used to determine the exhumation histories.

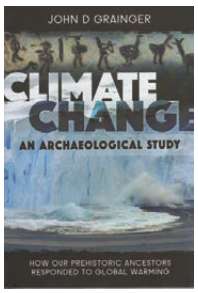
For me, the final paper was fascinating and, I have to admit, rather incomprehensible in equal measure. This work modelled the Earth as a body comprised of a theoretical material with special properties, known as a DG-2 material. In a highly mathematical treatment (it is not often that Einstein's equations are invoked in geology — and I don't mean E=mc2!) the expected deformation response of such a body is computed, and shows transitions from different styles of deformation at different depths, corresponding closely to the boundaries in the Earth, such as those at the base of the lithosphere and the discontinuities within the mantle. I am unable to do this paper justice as, quite simply, it would be a significant undertaking to acquire the amount of background knowledge required to understand it properly — and that is despite my having a PhD in mathematics. But the idea was an appealing one, and I feel it is something I may return to.

This book was certainly a worthwhile read, with much thought-provoking and insightful work that will develop your understanding of structural geology and make you question your interpretations in the field. The papers mostly fit the theme well, continuing on from Ramsay's original work using the same rigorous, quantitative and analytical treatment that seems to be developed in his work. Nonetheless, the book must be appreciated for what it is: a collection of scientific papers at the forefront of research. It is a challenging read and there is much detail that is beyond the reach of those who are not active in the field. However, if you are prepared to devote the time to it, your efforts will be rewarded with a more nuanced understanding of rock deformation and a great respect for the researchers whose work enables us to unravel the geological history hidden in the rocks.

Abstracts of the papers, including the full text of the four Open Access articles, can be found at https://sp.lyellcollection.org/content/487/1/NP

— Michael Perkins, OUGS Scotland Branch Oraniser

Book Review



Grainger, John D. 2020 *Climate Change: an Archaeological Study. How Our Prehistoric Ancestors Responded to Global Warming.* Barnsley: Pen & Sword Books (ISBN 978-1-52678-654-8; vii + 288pp; hardback £25)

John Grainger, a well known Classical historian*, has ventured into wider historical explorations in this book. A seasoned writer, he joins the ever-growing number of popular authors writing about humans and climate change.

The Earth science credentials of this book — and thus its review in these pages — is that it covers the full sweep of the Palaeolithic, that is to say the Pleistocene, up to and including the early Holocene Neolithic developments in agriculture; and that his coverage is worldwide. And that it addresses global climate and environmental change in relation to humans.

The book could be called Archaeo-Earth science, for its aims are to describe and explain humankind's cultural evolution in response to climate and environmental change, and the growing effects of human culture on climate and environment.

However, Grainger begins with an 'Introduction' that clearly stamps himself as one who considers much of the publication about 'global warming' as over alarmist, and that much of it is downright inaccurate. Consider his opening statements: "Global warming, we are told, is a fact. Evidence is produced almost daily to support this theory … And yet it is actually not much more, so far, than a preliminary theory supplemented by projections of future trends, which vary widely with the hysteria of the projector."

Grainger does not deny that the Earth's climate is changing. Basically, he says that the evidence of climate change records is really only about two centuries [old], that this is merely the "blink of an eye" in climatological and geological terms; that the Earth has gone through periods of climate (and consequent environmental) change regularly; and that it is natural. While not denying that sea level rise is likely from the melting of ice caps and glaciers on land, he categorically dismisses any notion that the melting of Arctic ice will "seriously affect the sea level", labelling statements that it will as "falsehoods". To focus only on this one aspect and consequence of Arctic ice melt ignores a lot of what Arctic ice melting *is* causing in the wider climate change picture — and it's *not* OK — and obscures the full story (see Chelsea Harvey 2021 'Earth has lost 28 trillion tons of ice since the mid-1990s'[summing up years of research published earlier], *Scientific American* online, republished from *E&E News*).

These statements are simply made, and not backed up in any way with cited notes of sources. Each of Grainger's chapters ends with a Further Reading list — each of which consists for the most part of secondary sources that he has used to summarise the human cultural developments in the landscape of environmental changes throughout the Pleistocene and early Holocene.

But consider the way Grainger dismisses any need to cite sources for his sweeping opening statements about climate change research (p7): "Discussions of 'global warming' are already far too numerous to detail here, and are all too often ephemeral and inaccurate, overtaken or alarmist, and soon outdated." It seems to me to be unworthy of a scholar of John Grainger's alleged standing to simply sweep away in one sentence any need for *him* to source his statements of so-called 'fact.' Thus his further reading for this salvo of assertions and allegations about climate research consists of three books, dated 1977, 2004 and 2005.

Such categorical and opinionated statements about the huge amount of research, not to say about the scientists doing it, are, to me at least, outlandish and unnecessary to the book, and seem downright inapplicable and irrelevant.

Following the 'Introduction', a 'Prologue' opens the book with a detailed summery of the mid- to late-Pleistocene peopling of Australia. Thereafter the chapters cover: 'The Ice Age'; 'Following the Ice' [the Mesolithic warming]; 'Escaping the Ice' [migrations into ice-free regions, including all of the Americas]; 'Floods and Fish' [post-Pleistocene sea level rise]; 'Sedentary Foraging [early more permanent living and the development of territoriality]; 'Drought' [living in the deserts that changing climate created]; and finally 'Agriculture' [the development of permanent dwelling on larger scales and their effects on environment].

Grainger's style is fluid and he provides a reasonable summary of humankind's cultural endeavours through prehistory. All these chapters are based mostly on secondary sources, often relying on a preponderance of books infrequently stretching in date beyond the 1980s and 1990s, or early 2000s.

The book is liberally illustrated with line maps — all greyscale — and greyscale drawings, charts and graphs. Following each chapter, except for Chapter 4 'Floods and Fish', there is a 'Gallery' of selective black and white pictures. There is also a short Index.

Grainger finishes with a 16-page 'Conclusion' chapter. In it he focuses on the Mesolithic period as the time when the real last global warming occurred and asserts that people around the world in various states of cultural evolution primarily reacted conservatively to it — that, "in all cases by the wish of people to change as little as possible", which he considers to be "a universal impulse" (p270). After summarising much of what has already been said in the book's main chapters, he launches into a seemingly optimistic set of solutions, based on lessons demonstrated to us in solutions implemented by our early Holocene predecessors. Basically: technological invention and ingenuity: "The adaptability and inventiveness which [sic] are so clear in the Mesolithic Age will be the prime requirements for surmounting the climate problems of the Industrial Age" (p283). Without providing any specific concreted examples such statements remain platitudinous.

Grainger acknowledges that, "The issue of global warming, in so far as it is a human product and not merely a natural alteration … is one result of the industrialisation which [sic] has taken place over the last two centuries", but that, "industrialisation has also been the main engine for lifting the great majority of humanity out of poverty" (ibid.). He asserts without question both "so there can be no question of the Luddite response — destroy the machines" and that "A Luddite destruction of industry might solve the global warming issue, though that is by no means certain", but that doing so "is quite certain [to] condemn the great majority of people in the world to an early death, and the majority of the survivors to poverty" (p284).

These statements are primarily in response to this suggested destruction of the machines by "some of the more extreme 'green' advocates" (ibid.). It seems that, as he began his book,

Grainger is setting up hobby horses and knocking them down without presenting much evidence other than his admiration for human technological invention and ingenuity.

Thus his ultimate conclusion is that, "The only real 'lesson' which [sic] the global warming of the past has for us, therefore, is that experimentation and human adaptability are the keys to the present predicament." And his final solutions are that, "The answers in the future will be … biological and technological" and that, "one of the expedients is likely to be exploration of the solar system and human settlement on the other planets, and perhaps space stations" (ibid.).

In other words he doesn't really explain a solution, but rather reverts again to sweeping statements that seem more what he believes or hopes for than what research is showing us. There is no doubt that he is an optimist, and believes that we will find a way to adapt.

In summary, the descriptive chapters that form the bulk of the book are a useful compendium of human cultural evolution during the latest geological periods. But I have misgivings about the usefulness or purpose of Grainger's propensity for sweeping, opinionated, unsubstantiated assertions in his opening and concluding chapters.

* He holds an OU BA and post-graduate degrees from the University of Birmingham.

— Dr David M. Jones, OUGS Proceedings Editor

Book review

Moss, John 2020 *A History of Placenames and Where They Came From*. Barnsley: Pen & Sword Books (ISBN 978-1-52672-284-3; xix + 388pp; hardback £25)

It is remarkable the richness of physical geography (aka earth science) that has become 'hidden' in the naming of places, the study of which is toponymy.

There have been several books on place names published in the past few decades, with various areas of coverage, either wider or narrower than John Moss's book. And of course there is even, for the place names of the United Kingdom, an official Gov.UK website for them.

Moss's opening sentences in his Foreword belie the impression that most place names are derived from people. In fact, many, if not most, are combinations of personal names, words from the different languages of settlers and migrants into England, and geographical terms — both physical and biological.

I would not say that Moss's book replaces the classic Eilert Eckwall *The Concise Oxford Dictionary of English Place-names* (originally published in 1936, 4th edn 1960; last reprinted in the 1970s and now out of print). But John Moss's book will provide a useful addition to your reference shelf if you do not posses Eckwall, or even if you do. Moss is honest in explaining that his selection of entries is 'personal'; and his coverage includes most of the principal places one is likely to encounter in England. Also, a main difference between these two books, and why I say they are *both* useful on the reference shelf, is that Moss's entries are for the most part longer than Eckwall's; and of course, include the benefit in many cases of research and discoveries since Ekwall was last up-dated in 1960.

Writing a review of this seemingly unlikely book for a geology journal is not so incongruous as you might think. For many place names, as mentioned earlier, contain so many physical elements as well as personal and language terms. To consult this book in combination with your walks and travels will give you many insights not only into the wealth of various languages from which English now makes up its vocabulary, but also insights into the physical natures of many places, which may not be evident now. Examples include elements such as 'ley', 'copse', general names for topographical features, water bodies and the like. Often, although such elements were used to name places in the past, notably when settled, many such places now no longer bear much resemblance to their original descriptive terms.

I'll give only one example, chosen because it illustrates what I have said above, and because it so closely relates to an example I can give for my own neighbourhood. 'Catford' in London's Lewisham district was once a wooded area. A settlement was established there, where the river was fordable and where the settlers noticed the presence of willcats. The place name of a local 'suburb' of where I live in Godalming — Cattishall — contains similar geographical information: a hill frequented by wildcats. Needless to say, sadly, wildcats are no longer present in either location (other than perhaps examples of *Felis silvestris catus*-once-domesticus gone semi-feral).

A further major difference of Moss's book to other place-name books is its arrangement. After his Forewared, Moss first provides a useful Glossary of common terms that relate to the *Doomsday Book*. This is followed by an equally useful listing of common elements frequently included in English place names from Old English, Old Norse, Middle English and Old French, and Celtic languages.

There follows a potted history of 'Migrations and Invasions', including useful maps, and then two short essays on 'Placename Origins' and on 'Land Ownership and Tenancy' (especially relating the book to the Doomsday survey).

Thereafter, the book consists of place names listed alphabetically in Parts 'Five' to 'Fourteen', dividing up the country and each with a reference map: North-East, North-West, West Midlands, East Midlands, East Anglia, The Home Counties, Greater London, South-East, South-West, and British Islands. A final Part is 'Novel, Odd, and Unusual Placenames', which contains an entertaining and amusing selection.

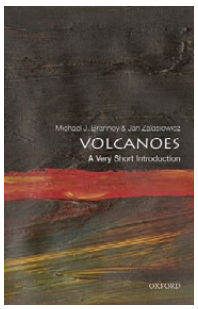
The book concludes with a Bibliography and an Index.

This book is not one for reading cover to cover, but rather one for the gentle pastime of 'dipping into'. It is for before, during and after a journey or a walk, for those wanting to know the derivations and etymologies, and some interesting historical background to the names of places passed through or seen on the map. I consider the book's price a modest outlay for so much gain.

— Dr David M. Jones, OUGS Proceedings Editor

Book review

Branney, Michael J., and Zalasiewicz, Jan 2020 *Volcanoes: A Very Short Introduction*. Oxford UP (ISBN 978-0-199-58220-4; 184pp; paperback £8.99)



This book is part of the extensive series entitled 'Very Short Introductions', which are written by experts for anyone wanting a stimulating and accessible way into a new subject. Although not aimed at geologists, it would also provide a quick revision on many current volcanological aspects to those who studied geology some time ago.

It is a small book, approximately A6 size, thus not many words of text on each of its 184 pages. The 50 black and white illustrations include many photos of volcanoes worldwide, together with clear sketch diagrams explaining volcanic processes.

The book is divided into nine chapters. The first four cover the making, mixing and eruption of magma, and the different volcanic products found in various tectonic settings. Chapter 5 focusses on what happens to volcanoes after eruption and how the edifice is changed by such things as erosion, landslides and earthquakes.

Chapter 6 describes older, mainly extinct, volcanoes, which help scientists to understand how volcanoes are formed by studying the features and chemistry of the rocks. This section includes some familiar volcanic areas in the UK where British volcanologists, including one of the authors, painstakingly unravelled the complicated eruption histories evident in Snowdonia, Glencoe and the Lake District, which later helped towards the understanding of volcanic eruptions worldwide.

Chapters 7 and 8 consider how volcanoes interact with humans and other living things, and particularly the hazards and benefits of living near volcanoes. Finally, Chapter 9 travels into space to look at volcanism on other planets.

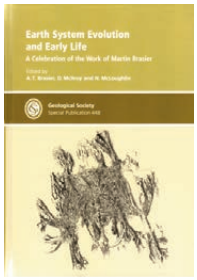
All processes and concepts are explained in a clear understandable way with a minimum of technical terms, although these are also defined in the short Glossary. Throughout, there is clear reference to how these facts have been obtained using geophysics, laboratory experiments and field observations.

When I was asked to review this book, I thought "not another book on volcanoes", but was impressed by the mix of well-known volcanic science together with some cutting-edge theories, some which were new to me.

For example, Chapter 3 covers how water increases the explosivity of eruptions and includes an explanation of how peperite is formed when magma is erupted into soft, wet sediments. But this theme is then expanded to include details of how peperite can also be formed within water-saturated solid crust. Here, hot magma ascending through pores and cracks creates steam explosions resulting in disaggregated rock and ultimately space for the magma to quietly fill after the steam has moved on. This could certainly explain some puzzling mixes of peperite, lava and breccias seen in the Borrowdale Volcanics of the Lake District.

Altogether, a little gem of a book and well worth the modest cost.
— Chris Arkwright, BA Hons (Open), MSc (Man), PhD (Man), FGS

Book review



Brasier, A. T., McIlroy, D., and McLoughlin, *N. (eds) 2017 Earth System Evolution and Early Life: a Celebration of the Work of Martin Brasier*. London: Geological Society Special Publication 448 (ISBN 978-1-78620-279-6; 432pp; hardback £120)

This Geological Society Special Publication is a Festschrift for Professor Martin D. Brasier (1947–2014).
It comprises 23 papers, seven of them co-authored by Prof. Brasier himself. An opening remark in the 'Dedication' is testimony to his scholarly achievements and his humanity: "Some of the best stories were those Martin read to us directly from narratives found hidden within complex patterns in rocks and fossils."

Following an opening paper, the structure of the book is given by organisation of the papers into four groups:

- Deciphering the earliest evidence of life
- The preservation, origins and interactions of early multicellular organisms — the Torridonian Supergroup, NW Scotland
- Progress on understanding the evolution of animal life and the biosphere during the Precambiran–Cambrian transition
- Studies of exceptional preservation

The papers are without exception detailed and erudite, each ending with extensive source reference lists, but all readable. Anyone interested in the earliest development of life on Earth will gain from them, but they are not bed-time reading!
The opening paper describes Martin Brasier's long participation in the search for life's earliest appearance and first evolutionary steps towards higher biological organisation. The collection of papers that follows focuses on two crucial aspects in that pursuit: (1) cellular preservation of early microbial life and (2) the evolution of the first Ediacaran macroscopic life forms. Equally, the requirement of exceptional preservation is addressed in describing the use of state-of-the-art techniques for the identification of earliest life and analysis thereof.

The end photograph in this first article — the packed crowd of Prof. Brasier's 'Academic Family and friends' at the celebration when he retired — literally depicts the breadth and extent of his achievements. Apparently, he also played jazz piano!

The first group of three papers focuses on fundamentals: Brasier's establishment of the framework for discussing and defining 'earliest life', declaring that the burden of proof lies with the claimant rather than with those who would refute the claim, and the clear establishment of 'rules' for formulating hypotheses to test the evidence. The succeeding two papers are more technical, describing in detail X-ray microtomography and micro-X-ray absorption spectroscopy techniques. I found the paper on using micro-X-ray absorption spectroscopy to identify and investigate trace fossils in Archaean pillow lavas in the South African Barberton Greenstone Belt particularly interesting.

The next group of four papers is dedicated to the study of earliest life in the Torridonian Supergroup of north-west Scotland. While not the very oldest setting (*c.* 1,200–600Ma) for early life on Earth, these Torridonian studies demonstrate the use of techniques — spectroscopy, morphological and chemical analysis, and evaluation of preservation — to reveal a transition in microbial life forms of some of the earliest Proterozoic eukaryotic life, including on land.

The third groups of 12 papers forms a characteristic Festschrift of studies embracing Prof. Brasier's wide interests. The focus, as indicated in the section's title, is on the Precambrian–Cambrian transition, especially on the Ediacaran. Several papers focus on determining the date and nature of the Precambrian Phanerozoic–Ediacaran boundary, the environment on Earth during the transitional period, and on its importance and effects on the development of early life. These papers look at evidence from several continents (one paper of 20 pages of text is followed by 19 pages of references!)

Further papers are studies that range the globe and include northern China (identifying and measuring 'the Great Unconformity'); Namibia (Ediacaran metazoan reefs); south-west Britain, southern Ireland and eastern North America — aka the ancient Avalonian microcontinent (Ediacaran macrobiota, early evidence of chemosynthesis, and one of the first examples of 'ecosystem engineering'); the Charnwood Forest, UK (classifying rangeomorphs); Shropshire, UK (Ediacaran biota 'microbial trapping', '*intrites*' as an example of ecosystem engineering); and northern Norway (the 'Cambrian explosion' in the Ediacaran–Cambrian succession).

One paper describes and examines post-fossilisation processes on Ediacraran macrofossils.

And one paper, particularly fascinating to me, is a study of Cambrian explosion 'engineering': the study of trace fossil 'ichnotaxa' types, burrow shapes, complexity, depth, function and bioirrigation to engineer one's ecosystem!

The final group of three papers further shows Prof. Brasier's depth of interest. Two papers leave the Ediacaran behind and bring the reader to the Cretaceous — one on fauna, one on fauna/flora. We learn about an exceptional example of brain tissue preservation of an Early Cretaceous iguanodont; and about six Early Cretaceous 'amber-coloured' fossils from southern England that show structures interpreted as insect cocoons (at least three of them) and plant seed pods (at least two of them) — fascinating.

The final paper is not about life, but rather an analysis of Early Cretaceous to Oligo-Miocene amber. Infrared spectroscopy was applied to samples from 17 localities in America, Europe and Asia to reveal identification criteria.

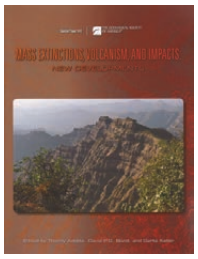
A few of these papers are heavily laden with statistical data. But throughout the book there are numerous sketches, drawings, photographs and micrographs of specimens; and there are numerous useful maps, graphs and logs, and explanatory cartoons — many in colour. All are well produced and clear in print.

The book ends with an eight-page Index to help the reader get back to where related information is scattered among the papers.

While not denying that the book is expensive, it truly contains a wealth of fascinating information to those who seek it.

— Dr David M. Jones, OUGS Proceedings Editor

Book review



Adatte,Thierry, Bond, David P. G., and Keller, Gerta (eds) 2020 *Mass Extinctions, Volcanism, and Impacts: New Developments*. Boulder: Geological Society of America Special Paper 544 (ISBN 978-0-8137-2544-4; vi + 245pp; paperback US$60.00, available for £46.25 from the London Geological Society)

The Geological Society of America in Boulder, Colorado issues a similarly named series of conference volumes. This number is a truly international cooperation of geologists (one French, one British and one American), to edit nine papers presented in a topical session at the 2016 Geological Society of America Annual Meeting. Most of the papers are authored by multiple authors, often consisting of international teams and/or representing multiple universities.

The nine papers present some of the newest research at the time, on the topic self-evident in the book's title. As is to be expected with publications of this nature, the papers are technical. They cover detailed, intricate and heavily resourced research on geological events likely associated with environmental change and mass extinction, with papers on Ediacaran, Jurassic, Cretaceous and Cretaceous–Palaeocene (the K/T boundary) events. While not for the timid, those who venture within will be well rewarded with excellent research and insights into the roles of mass volcanism and the famous Chicxulub impact events and their results in climate and environmental change caused on Earth. The general approach is to investigate before, during and after each mass extinction discussed. While not a textbook for students, this volume is for reading lists, especially for later-year earth science and post-graduate students.

The papers are academic, so to quote their long titles and list all the authors would fill many lines.

The first paper, single-authored by Grzegorz Racki (University of Silesia), sets the scene for volcanism. Racki gives a tour de force account of the development of the current models showing the close correlation between four of the mass extinction and large igneous provinces (LIPs). He covers the progress of understanding from the late 18th century to the 1980s, dominated by adherence to the Lyellian uniformitarianist 'steady-state' paradigm before examining more recent reasoning behind the realisation of LIPs' association with 'progressive actualistic-catastrophic events — 'punctuated equilibrium'. Albeit occurring over long periods of time in human-life terms, these massive volcanic events were indeed more geologically rapid and impacting to disrupt the steady-state of climate, ocean circulation, greenhouse effects and oxygen levels compared to the state of these factors before and after the volcanism and correlated intense extinctions. The papers that follow are detailed examinations of areas and processes that have affected this change in interpretation of the global effects of LIPs.

The second paper investigates the Gaskiers glaciation in the late Ediacaran, establishing connections between glaciation ('Snow Ball Earth') and massive flood basalt deposition and climate change. The Gaskiers glaciation was an event of short duration (geologically speaking, between 1.6Ma and 340Ka) that occurred on at least 14 palaeocontinents (Laurentia, Baltica and West Africa). The authors document the multiple pulses in the Central Iapetus magnetic province and establish their synchroneity 580–570Ma with the Gaskiers glaciation, to propose that a first magmatic pulse triggered the glaciation, and that global warming associated with subsequent flood basalts from *c.* 579Ma to 570Ma helped to end the icd age.

A third paper investigates the Karoo Basin large igneous province in South Africa. The emplacement of these igneous sills represent degassing of CO_2 and CH_4 through breccia pipes. Mapping the distribution and nature of the pipes, the authors conclude that the rapid degassing process played an important role Early Jurassic climate change and oceanic anoxification.

The next paper examines association between the Early Cretateous Paraná-Etendeka LIP, and the north-western Tethys Sea and proto-North Atlantic Ocean. The authors compare this 'Weissert episode' with known anomalous high levels of mercury (Hg) in European Valanginian sediments (*c.* 140–133Ma) in the proto-Atlantic Vocontian Basin. They assert that this increased Hg sequestration is due to organic matter production in an oxygen-depleted environment and regional volcanic activity.

An examination of the Guerrero-Morelos carbonate platform of south-western Mexico relates it to the mid-Cretaceous Cenomanian–Turonian oceanic anoxic event 2 (OAE; *c.* 94–90Ma). Pre-dating the more well-known end Cretaceous mass extinction event 35Ma later, the authors nevertheless show the significant effects of sea-level fluctuations and $\delta^{13}C$ change on benthic foraminifera distributions. They correlate these fluctuations with biotic responses in pelagic environments in the UK Eastbourne region, showing the two areas and their responses to be synchronous.

The next paper takes us to that momentous Cretaceous–Palaeocene (K/T) boundary of *c.* 65.6Ma in an examination of shallow-water limestone formations globally. The authors look at the easternAlps in more detail, and compare its geological succession with similar carbonate sequence environments in Croatia, Oman, Madagascar, Belize and Guatemala, and with near-shore siliciclastic environments in Tunisia, Texas and Argentina, all dating across the K/T boundary. Planktic foraminiferal and other biological responses to these changes in marine transgression and subaerial exposure is compared to coeval deep-sea depositional patterns to better understand environmental change related to Deccan volcanism.

The seventh paper focuses on the K/T boundary and Deccan volcanism in the Indian subcontinent. Three geologists at the University of Delhi examine the evidence for the environmental stress believed to be related to the Deccan LIP. Close analysis of organo-molecular compounds from numerous geological successions dating to the volcanism helps to interpret the biological effects of the LIP and leads the authors to conclusions that also highlight the effects of regional wildfires induced by the adjacent Deccan volcanism, and the accounts for much of the regional mass extinction.

The following paper is also focused on the Deccan magmatic province, examining magnetic and mineralogical data of bole beds. These data, not surprisingly, reveal fluctuations in the magnetic patterns and mineralogical content across bole beds. Then authors attribute these variations to contrasting humid and dry environments during weathering, and that they represent a single weathering profile involving localised soil formation without external sources.

The final paper includes, again, analysis of the K/T boundary with evidence from the Deccan Traps LIP, and from the Chicxulub asteroid impact event. This is a wider-ranging study in which the authors examine the environmental and biological consequences of the two catastrophes, using a 'climate-carbon-biodiversity coupled model called the ECO-GEOCLIM model'. They studied temperatures, pH and calcite saturation states and their effects on productivity and biodiversity changes responding to drastic, sweeping environmental change. Their results show that the combination of the two events of massive volcanism and a 10km-diameter impactor would have caused (1) a 3.5˚C global warming, (2) a rising CO_2 concentration to +470ppmv, (3) short intervening periods of 'sulphate aerosol 'shielding effect' cooling, and (4) decreasing oceanic surface pH from 8.0 to 7.8, and deep ocean pH decrease from 7.8 to 7.4. In biodiversity, this cataclysmic combination caused the biomass and biodiversity of calcifying species by *c.* 80%, and that of non-calcifying species by *c.* 60%.

Each paper is supported by a lengthy references list, as expected. However, as for an issue of a journal there is no attempt to provide an index. Every paper is accompanied by numerous illustrations, graphs, charts and explanatory geological cartoons. These are all well produced and legible; some of the papers include massive data charts. The paper stock is durable but not high-gloss, and as a paperback these factors make possible a much lower price than similar volumes of conference papers.

— David M. Jones, OUGS Proceedings Editor

Book review

Robb, Graham 2016 *Cols and Passes of the British Isles*. London: Penguin (ISBN 978-0-141-98145-1; 240pp; paperback £9.99)

Although we were not sent this book by the publisher for review, I decided to write one about it, as I was gifted a copy, and because it is such an unusual book with geological and physical geographical content. In addition, it involves cycling, a pastime that I am aware some of our members enjoy as well as their geological interests.

The subject of the book is self-evident in its title. What is nearly unique about the book is that the subject matter had seemingly never been seriously addressed before. In the author's own words in his Prologue (page 9):

This book was already well down the road, composing itself at a leisurely pace, when it struck me that it ought to be heading somewhere in particular. The writing mind caught up with it, pushed a little harder and, after thousands of miles and two years in the workshop, a brand-new reference work was ready to be wheeled out: the first complete guide to the cols and passes of the British Isles.
… it seemed incredible that a whole aspect of the cultural and geographical heritage of the British Isles had remained undiscovered or, at least, undescribed.

The no doubt muscular-legged Mr Robb had set out to locate, ride or push his bike over, list and describe every col in the British Isles! He describes his discovery that there was already a French madness for cols, even a club for it promoted by 'le Club des Cent Cols'; and to the shame of *les Anglais* that the French had actually produced a list of "the 533 cols of the British Isles"!

Robb states that, "The definition used in this book is the geological definition. Every col identified in this catalogue is a true col in the scientific sense." (page 16). Thus he explains that 'col' and 'pass' are not interchangeable: "'Col' is scientific; 'pass' is a vague umbrella term applied not only to cols but also to a great variety of passages and crossings." (page 17). There are no fewer than 2,002 cols in the British Isles, and even one in London (Sydenham Rise in Forest Hill, page 120).

The book describes various 'types' of col in the sense of their shapes, sizes and distinctive characteristics. Then Robb explains how he compiled The Catalogue — an interesting account of his careful examination of OS maps, place names and literary references, and the discovery that there are 138 variant terms (or 172 if you count variant spellings) of what is a col. The most prolific source of col names turned out to be the first series of OS maps: Ireland 1827–46, Scotland 1842–82, and England and Wales 1842–93. A map of all 2,002 cols (page 15) shows that the distribution of cols in the British Isles reveals a decided concentration to the west, although fairly evenly sprinkled around Ireland. Could this have anything to do with the geology — hmmm?

And do not be fooled into thinking that the single black dot out to the left — seemingly in the middle of the Atlantic Ocean offshore of the Outer Hebrides — is a sloppy printer's ink mark. It is St Kilda, which boasts no fewer that three cols: Am Blaid, The Gap, and Mullach Mòr–Conchair, all on Hirta (pages 190–2).

A Glossary explains the various language and area abbreviations used, and lists every recorded term for a col. The next chapter tours the Regions, and includes sketch maps of various concentrations of cols. Then a brief chapter of Superlatives: 'highest', 'lowest', 'steepest', 'tastiest', 'remotest' (obviously the cols of Hirta), 'earliest recorded' (Swuran Tune, *c.* 970 AD), 'the oldest and the youngest', and 'the ugliest and the loveliest'.

References used to identify all the cols are listed on pages 95–9.

And then comes, The Catalogue.

After a brief explanation of terms and how the catalogue is organised there follow 128 pages listing every col across two-page opposing spreads, including columns for its Name, Elevation, Surface, Nearest place, Region, Latitude and Longitude, National Grid reference, and Notes. It is divided into five sections: England, Wales, Scotland, Northern Ireland, and Republic of Ireland. Each of these is in turn subdivided, alphabetically, into counties, and in some cases into 'mainland' and 'islands' sections.

Like a dictionary, The Catalogue has key-word headers for finding a region quickly.

A short Index of "some of the better known cols and passes" completes the book.

The book's format is narrow and tall, easier for packing on trips to conquer cols; but whether you cycle or not, this is an intriguing book to just sit and pore over!

— Dr David M. Jones, OUGS Proceedings Editor, also avid trekker and cyclist

Obituary

Eddie Yeadon — an appreciation

This is not a formal obituary. I knew Eddie only at LOUGS, and like many of you I was very sad to hear that he had died a few weeks short of his eighty-third birthday. He was a good friend and colleague and his time with LOUGS coincides with mine. I always thought of him as a 'real' scientist, whereas I, through a lot of hard work, just about managed!

We took several courses at the same time in the early 2000s and indeed were at the Kindrogan week together. He was always helpful, amusing and kind. We attended the same tutorial groups and it was always a pleasure to see him.

His back story I give briefly here thanks to his daughter, Anne Owens.

After schooldays at Chorlton Grammar School, Manchester, he studied Physics at Manchester Institute of Science and Technology, eventually gaining a PhD.

I now quote verbatim from her e-mail: "His career as an engineer and physicist took him for several years to the USA in the 1960s, where he worked on the visors for the helmets used in the Apollo 11 Moon landings. He also designed a reflector left on the Moon to bounce a laser beam. He joked that this was the part of the mission that didn't work (although it did eventually). After returning to the UK he began work with Mullard, developing night gun sights for M.O.D. This was successful and his name is on the patent for this item. He subsequently worked in R&D for Crossfield Electronics on the lasers for high-spec printing and scanning machines.

His retirement allowed him to indulge his interests in astronomy and maritime history, volunteering at the Royal Observatory Greenwich and co-founding the Flamsteed Astronomical Society in 1999, serving as its first chair. He organised a popular event to view the 2004 transit of Venus, guided many guests around the Observatory and gave talks on subjects as diverse as the Hubble Space Telescope and the Measurement of Time by astronomy."

At LOUGS he served on the Branch Committee as Treasurer, with numerous explanatory graphs at the AGMs! He gave talks on phenomena he had observed on his travels to places from the USA to the Arctic to Patagonia. At lectures his questions were always knowledgeable and to the point. He was a friendly participant on field trips, and indeed gave some of us a tour of the Royal Observatory.

He is survived by his wife Janice, two daughters and three grandchildren. Our sympathy to them in their sad loss. He will be missed by many of us for his friendly presence and witty comments, when we eventually get back to meeting as a group.

— Yvonne Brett

Obituary

In memory of Sybil Richardson

(13/05/1933–9/03/2020)

Sybil was one of the early students of the Open University, graduating with a BA (Hons) in December 1984. Although Sybil studied science subjects, the OU were prevented from awarding the BSc until many years later.

Sybil was a founder-member of OUGS Walton Hall Branch and became actively involved in arranging field trips and many other aspects of Branch management. She served as Branch Organiser briefly in 1984. In 1994 she moved north to Lancaster, and joined the North West Branch, and later on still, after moving to Portishead, joined the Severnside Branch. She served as OUGS Sales Officer from 1994 to 2000. Always game for a field trip, Sybil joined many excursions all over the UK and Europe, and nearly always attended the OUGS Annual Symposia.

Being a forceful defender of Students Rights, Sybil served on many committees of the OU Students Association (OUSA).

In 1999, with her interest in Astronomy and her usual enthusiasm, she started an OU Astronomical Society (OUSAPS). Unfortunately, it foundered after a few years — field trips were limited. Unlike geology, it couldn't be so hands-on. However, there were some fun study trips to Portugal, staying at a specialist Astronomical Observatory (C.O.A.A.). It was very relaxing, viewing the stars by night, and exploring rocks, historical towns, botanical gardens, museums and local industries by day.

If there is one word I would use to describe Sybil, it would be 'Enthusiastic'. She approached all of her interests and projects with an enquiring mind and a passion. Her interest in geology stayed with her until the end. Sadly, suffering with mild dementia she moved into a care home in 2018. However, she took many of her precious rock specimens to decorate her room, 'of course I have them' she said when it was commented on! Sybil was a good and generous friend, fun to be with, gregarious, and very independent. We miss her.

— Linda McArdell

Obituary

In Memory of Graham Arrondelle a former OUGS Oxford Branch Member

Graham was a long-standing member of the Oxford Branch and was the Branch Newsletter Editor for four years from January 2010 to January 2014.

He regularly attended Oxford Branch events, including day and longer trips, the lectures and the AGM.

He organised the Branch Isle of Wight trip in 2011, which involved us seeing dinosaur bones in the museum and then 'real live' dinosaurs walking through the streets of Sandown on 5 November, see attached photo.

The second photo is of Graham on an Oxford Branch trip to Chicksgrove Quarry in 2012.

Sadly his health started to deteriorate as he suffered respiratory problems, so could no longer go on day or longer trips, but he still attended the lectures in Reading and Oxford until the closure of the Branch.

Graham and I used to car-share to the Reading lectures and had many a long chat putting the world to rights during these journeys, especially if Reading were playing at home and we encountered long queues on the M4.

His other main interest was the MG car club where he also did a stint as [their] newsletter editor, obviously practising for when he took over for the Oxford Branch.

Graham was a very gentle man with a lovely sense of humour. Graham sadly passed away on 11 June 2020.

— Sally Munnings; photos courtesy of Chris Phillips

The Society notes with sadness the passing of the following members in 2020 and early 2021:

Anne Andrews (West Midlands)
Grahame Arrondelle (Oxford)
Eddie Cheshire (Wessex)
Nigel Combly (Walton Hall)
Charles Jackson (Wessex)
Nicole Lloyd (West Midlands)
Brian Nash (Walton Hall and Oxford)
Hamish Nicholson (Sctoland)
Carolyn Pascall (London)
Sybil Richardson (Walton Hall, North West, and Severnside)
Wilf Walker (London)
John Wilson (Scotland)
Eddie Yeadon (London)

Editor's notes to contributors

Following are guidelines for the submission of articles to the *Proceedings of the OUGS*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Proceedings*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention — I will probably spot them anyway — so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Proceedings* articles

As *OUGS Proceedings* Editor I do not want the publication of your article to be more work than is necessary for you (or for me!). Your article need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material you are writing about.

Regarding articles from the presenters of lectures at the OUGS AGM and Symposium, all OUGS members are grateful to you for presenting a lecture to us on your research, and for agreeing to submit a version of your talk for publication in the *Proceedings*. The purpose of this is to make your information available to OUGS members and others who could not attend the Symposium. As OU students and OUGS members we enjoy hearing and learning the information these events bring to us.

All that is necessary are:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Proceedings* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can identify and set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your article, it may be a good idea to send one with these items marked up or otherwise highlighted. I can accept electronic files attached to e-mails, text and image files on a CD or on a flash drive, or via shared media.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 300dpi minimum for colour or half-tone images; as high a dpi as possible, please, for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 30. Obviously as an AGM or Symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to publish with your article — again, usually 10 to 30 is only a rough guide.

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.
As the author, this responsibility is yours.

• Please do *not* embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustrations should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD or flash drive: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs. Alternatively, a digital sharing package can be used, such as Dropbox or similar.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a website), full title, periodical volume or number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you as necessary as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3rd edn). Cambridge: Cambridge UP

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2nd edn). Oxford: Oxford UP

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford UP

Please feel free to contact me at any time about your article:

Dr David M. Jones, *OUGS Proceedings* Editor, 41 Blackburn Way, Godalming, Surrey GU7 1JY; 01483 424308;
proceedings@ougs.org

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OUGS Moyra Eldridge Photographic Competition 2020

Winning and Highly Commended photographs

Popular Vote Winner

The prehistoric forest on the beach at Borth, west Wales, taken in June 2019 at low tide when it was particularly well exposed following storm Hannah in April. The tree stumps and trunks have been dated to 4,500–6,000 years before present. They are a mixture of pine, oak, alder and birch, which have been preserved by being buried in acid anaerobic conditions in peat.

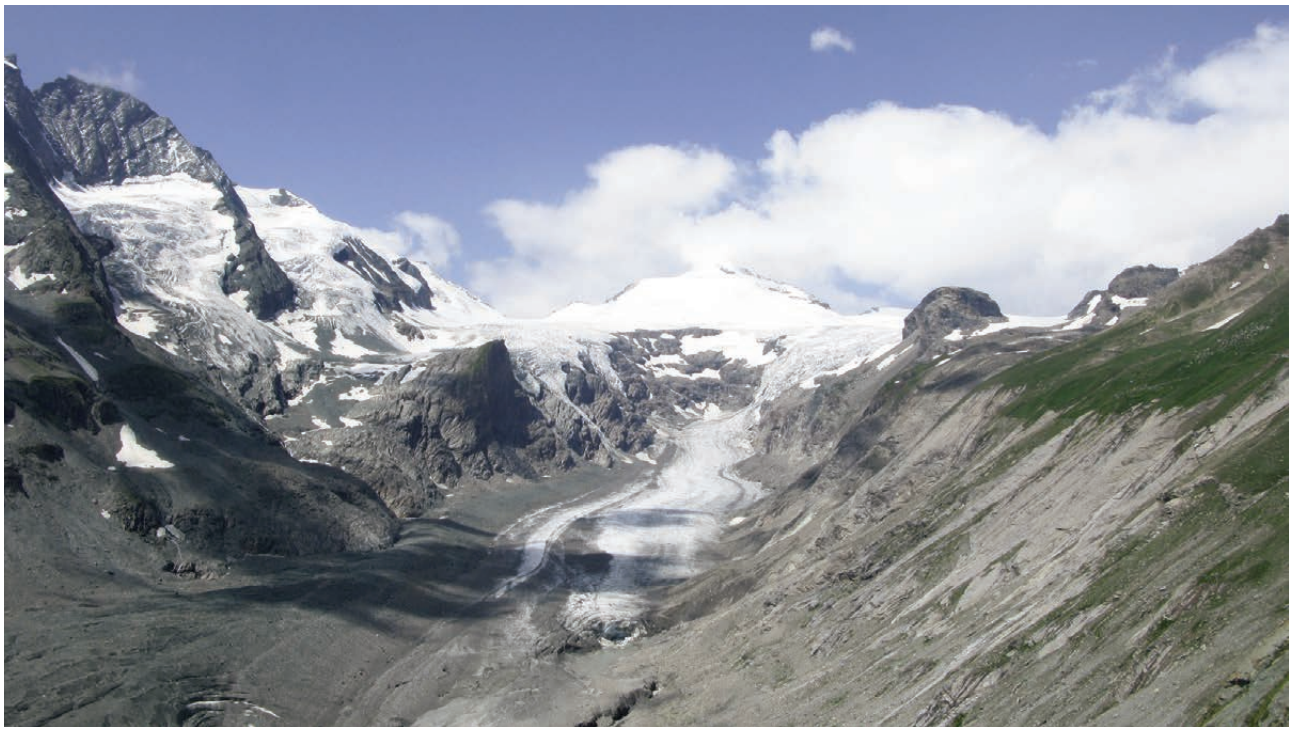
Geologically inspired landscape, structure or feature in the British Isles, Winner — Ian Williamson

Dun Caan is the highest hill on the inner Hebridean island of Raasay, and a good example of a landscape shaped by differential rock weathering and erosion. Resilient mid-Palaeocene basalt lavas form the summit crags, whereas the flanks comprise various 'softer', less resistant Middle Jurassic marine strata, including, in the foreground, glacially sculpted exposures of the Bearreraig Sandstone Formation. A Palaeocene dolerite sill showing some columnar jointing forms the prominent mid-slope crags.

Geologically inspired landscape, structure or feature, British Isles, Highly Commended — Sandra Morgan *These highly folded rocks of the New Harbour Group were observed at Trearddur, Anglesey. The New Harbour group was deposited in the late Cambrian and Early Ordovician. This was formed from sediment that had been eroded from island arc volcanoes. It was folded and deformed first during the Caledonian Orogeny and later in the Variscan Orogeny.*

Geologically inspired landscape, structure or feature, British Isles, Highly Commended — Stuart Swales *Nessend, Holy Island. Sandbanks Limestone above Acre cyclothem.*

Geologically inspired landscape, structure or feature anywhere else in the world, Winner — Franco Zicchieri
“Tourists standing on the crater lake rim”. Whakaari (white island) is an active submarine volcano with just the summit above water. It is c. *40km from the mainland in the Bay of Plenty, New Zealand. Tourists are taken around in groups, this image shows some standing on the edge of the crater lake, contemplating the beauty of the scene.*



Geologically inspired landscape, structure or feature elsewhere in the world, Highly Commended — Mark Sandy

The valley of the Pasterze Glacier, Austria. The valley lies below the Grossglockner, the highest mountain in Austria. The Pasterze Glacier has retreated considerably in recent decades. The valley lies within the Hohe Tauern region of the Austrian Alps.

Geologically inspired landscape, structure or feature elsewhere in the world, Highly Commended — Eileen Lawley

Surprise Glacier in the Denali National Park, Alaska is one of more than 26 glaciers ending in Prince William Sound, which is c. *100km long. Here there are more tidewater glaciers than anywhere else. The wall of ice that we see is 200m high and actively calving into the sea. The photo was taken from a (stationary) high-speed catamaran in 2019.*

Industrial geology, Winner — Sandra Morgan

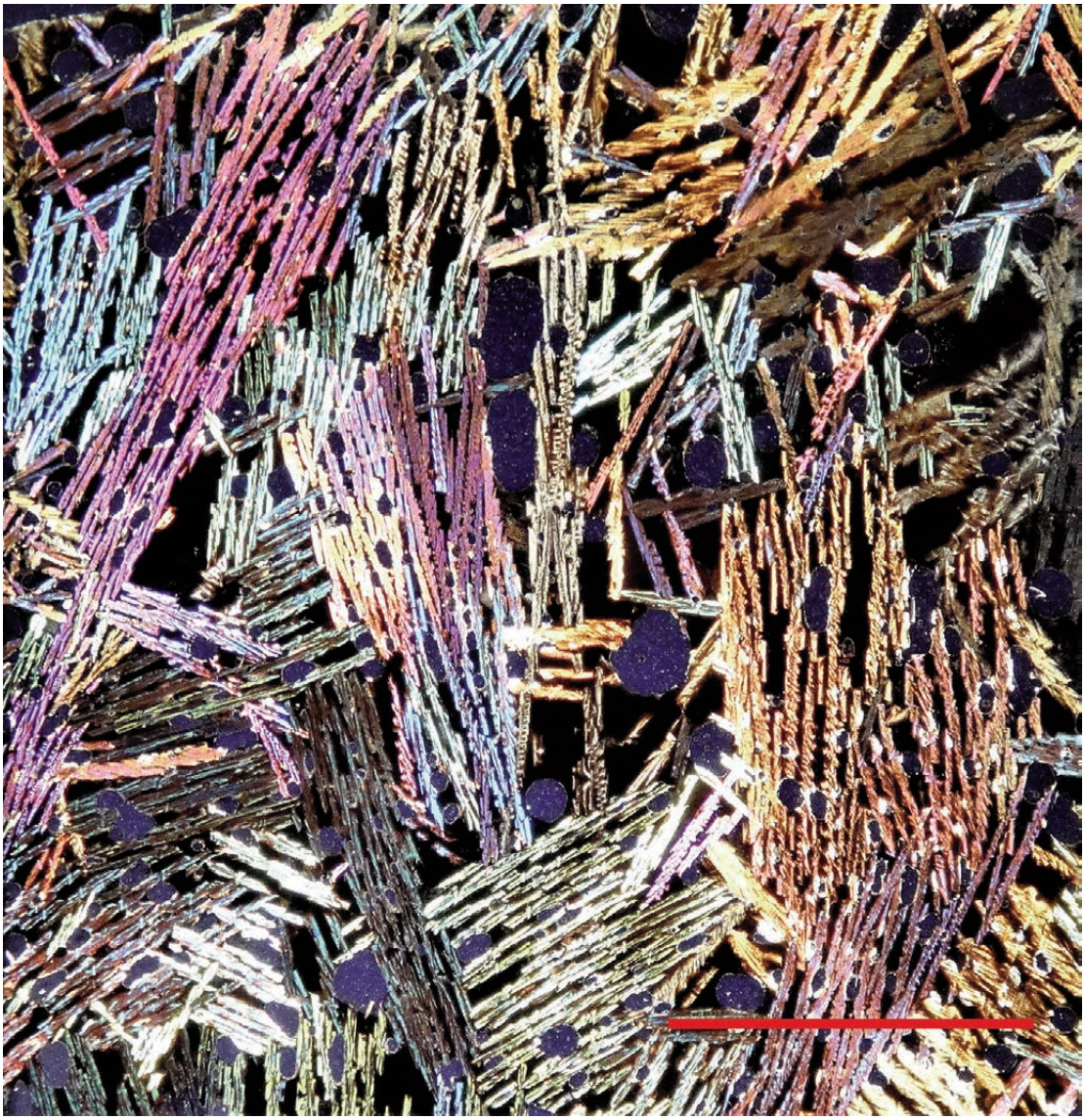
The Vivian Slate Quarry is part of the Dinorwic Slate quarries at Llanberis, North Wales. The image shows some of the galleys — stepped working levels cut into the hillside at intervals of approximately 60ft (18.3m), with the bottom level cut into the ground. The quarry was open by 1873 and closed in 1960. Since then, run-off and underwater springs have filled the quarry to a depth of up to 18 metres.

Industrial geology, Highly Commended — Sandra Morgan

Sygun Copper Mine in North Wales is a Victorian copper mine, which closed in 1903. The first extraction of copper took place where the veins of ore outcropped at the surface, possibly as early as Roman times, but deeper tunnels were made during the 18th and 19th centuries. The principal ore was Ordovician chalcopyrite (copper sulphite). Since the closure of the mine, water percolation has promoted the formation of quick-growing stalagmites and stalactites of ferrous oxide.

Industrial geology, Highly Commended — Eileen Lawley

The volcanoes that formed Lipari have not been active for about 7,000 years. An obsidian flow erupted 9,000 years ago and became covered in a thick deposit of pumice. This was mined and exported all over the world until mining ceased rather abruptly in 2007. This was a very controversial and locally unpopular decision made after the Aeolian Isles became a UNESCO World Heritage Site and involved the loss of many local jobs. The mine gives the appearance of having been abandoned during the middle of a shift.



Mineral, rock or fossil specimen, or thin section/SEM view, Winner — Duncan Woodcock *The spinifex texture in this photomicrograph is defined by acicular crystals of the iron-rich olivine fayalite in a glassy groundmass, which is black in this view between crossed polars. The texture developed by rapid crystallisation from a liquid with few impurities that could have acted as nucleation sites, allowing unimpeded growth of the few crystals of olivine that did nucleate. In this case the liquid was slag from Carnforth Ironworks. Spinifex texture is named after a similar-looking desert grass found in western Australia, where this texture develops on a larger scale within Archaean ultramafic extrusive rocks known as komatiites.*

Mineral, rock or fossil specimen, or thin section/SEM view, Highly Commended — Mark Sandy
Sectioned and polished ammonite.